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APPLICATION OF RADIATION AND LAG CORRECTIONS TO TEMPERATURES MEASURED WITH THE METEOROLOGICAL OFFICE RADIO-SONDE

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In a previous paper[1] the writer described a method of deriving the radiation errors of the Meteorological Office radio-sonde from the rates of absorption of radiation and loss of heat by forced convection by the temperature element and its shield. The purpose of the present paper is to describe the practical application of the method to the routine measurements of the upper air temperature.

The simplified expression for the temperature error is

$$S - T = \frac{Q}{q} - k\frac{dS}{dt}, \qquad \ldots\ldots (1)$$

where T is the true air temperature, S the observed temperature, Q the radiation absorption rate, q the heat transfer coefficient and k the lag coefficient or time constant (which is equal to C/q, where C is the heat capacity of the thermometer). The expression is simplified since each of the terms on the right-hand side should represent the separate effects of the thermometer element and its radiation shield. There are a number of factors which affect Q, q and k, and therefore the temperature errors, but which do not vary systematically. These are the absorption factors of the temperature element and its shield, the albedo of the earth, clouds and air below the radio-sonde, the rate of ascent and the swinging of the radio-sonde. All these may vary from one sounding to another but it is impracticable in routine work to take full account of the variations. The best that can be done is to adopt values which are representative of average conditions.

Variable factors affecting the errors.—*Absorption factors.*—The value of the absorption factors used in the previous paper[1] were obtained from laboratory measurements of random samples of the temperature elements and shields. So long as the materials and surface finish at present specified for their components remain unchanged the values for individual radio-sondes will not differ much from these values.

Albedo.—The radiation absorbed by the temperature unit after reflection from earth and cloud surfaces is roughly 25 per cent. of the total absorption. Variations in the albedo may therefore be quite significant. For example, a change of 0·1 in the albedo alters the radiation error by about 7 per cent., except at low solar altitudes where the effect is smaller. It is not practicable to estimate the albedo for individual soundings since, quite apart from the difficulty of estimating the amount of cloud visible from a radio-sonde, the measured albedos of apparently similar clouds are known to vary greatly.

The problem of the best value of the albedo to adopt has been facilitated by making estimates of the average albedos for each of the Meteorological Office radio-sonde stations. These estimates were obtained by taking the following average albedos of cloud, atmosphere and surface, based on the work of Fritz[2]:

Cloud ...	0·53	Air over cloudless area ...	0·11
Land ...	0·15	Air over clouded area ...	0·05
Water ...	0·09		

The relative contributions were then assessed from the annual mean cloud amounts and the proportions of land and sea visible from a radio-sonde at a height of 20 Km. and a distance of 50 Km. from its station in the prevailing wind direction. The results are given in Table I. They fall into two groups, the higher-latitude stations with an average albedo of 0·48 and the lower-latitude stations with 0·34. It is satisfactory to note that G. D. Robinson[3], using an independent method based on the surface measurement of radiation at Kew, obtained an average of 0·455 for south-east England, which may be compared with the figure 0·47 for Crawley in Table I. In view of the wide variations in cloud amount from day to day it is not considered worth while adopting different values for the two groups of stations. A single value of 0·40, instead of the 0·35 of the previous paper[1], has therefore been adopted for Meteorological Office stations.

TABLE I—ESTIMATES OF ALBEDO AT METEOROLOGICAL OFFICE RADIO-SONDE STATIONS

			Relative area "seen" from 20 Km. height			Contributions to albedo				Total albedo
			Cloud	Land	Sea	Cloud	Land	Sea	Air	
Camborne...	50·2°N.	5·3°W.	0·70	0·18	0·12	0·37	0·03	0·01	0·07	0·48
Crawley ...	51·1°N.	0·1°W.	0·68	0·22	0·10	0·36	0·03	0·01	0·07	0·47
Hemsby ...	52·6°N.	1·7°E.	0·71	0·15	0·14	0·38	0·02	0·01	0·07	0·48
Fazakerley	53·5°N.	2·9°W.	0·70	0·24	0·06	0·37	0·04	0·01	0·07	0·49
Aldergrove	54·7°N.	6·2°W.	0·70	0·18	0·12	0·37	0·03	0·01	0·07	0·48
Leuchars ...	56·4°N.	2·9°W.	0·67	0·10	0·23	0·35	0·01	0·02	0·07	0·45
Stornoway	58·2°N.	6·3°W.	0·77	0·09	0·14	0·41	0·01	0·01	0·06	0·49
Lerwick ...	60·1°N.	1·2°W.	0·78	0·07	0·15	0·41	0·01	0·01	0·06	0·49
O.W.S. I ...	59·0°N.	19·0°W.	0·79	0·00	0·21	0·42	0·00	0·02	0·06	0·50
O.W.S. J ...	52·5°N.	20·0°W.	0·77	0·00	0·23	0·41	0·00	0·02	0·06	0·49
Mean ...	...	... ...	0·73	0·12	0·15	0·38	0·02	0·01	0·07	0·48
Aden ...	12·8°N.	45·0°E.	0·30	0·49	0·21	0·16	0·07	0·02	0·09	0·34
Bahrain ...	26·3°N.	50·6°E.	0·20	0·48	0·32	0·11	0·07	0·03	0·09	0·30
Benina ...	32·1°N.	20·3°E.	0·35	0·39	0·26	0·19	0·06	0·02	0·09	0·36
Habbaniya	33·4°N.	43·6°E.	0·23	0·77	0·00	0·12	0·11	0·00	0·09	0·32
Malta ...	33·8°N.	14·5°E.	0·39	0·24	0·37	0·21	0·04	0·03	0·08	0·36
Nicosia ...	35·1°N.	33·3°E.	0·30	0·42	0·28	0·16	0·06	0·03	0·09	0·34
Gibraltar ...	36·1°N.	5·3°W.	0·41	0·35	0·24	0·22	0·05	0·02	0·08	0·37
Mean ...	...	... ...	0·31	0·45	0·24	0·17	0·06	0·02	0·09	0·34

Rate of ascent.—The radiation error varies inversely as the square root of the rate of ascent of the radio-sonde, except in the lower levels where the error is, in any case, small. The rate of ascent normally used at present averages 6 m./sec. (1,200 ft./min.), but there is a standard deviation of 7 per cent. which therefore gives a corresponding variation in the radiation error of 3·5 per cent. There is generally, also, a systematic change with height with a maximum at the tropopause which may be 15 per cent. greater than near the ground or high

in the stratosphere. For the purpose of computing the radiation and lag corrections the rate of ascent of 6 m./sec. has been adopted, but if for special purposes a very different rate is used the appropriate corrections can be obtained by multiplying the standard corrections by the square root of the ratio of the standard rate of ascent to the actual rate.

Swinging of radio-sonde.—In the previous paper[1] it was assumed that the average half-amplitude of swing of a radio-sonde from the vertical is 30°, and graphs were given showing the effect of this on the amounts of direct solar radiation absorbed by the thermometer element and its shield for solar altitudes between 0° and 90°. No allowance was made, however, for the fact that at solar altitudes below 30° the swinging of the radio-sonde allows some direct radiation to enter the bottom of the shield where it is reflected on to the thermometer element. The effect of this, which is relatively large at solar altitudes below 20°, has now been taken into account in calculating the total radiation absorbed, the revised figures for which are given in Table II and supersede those of Table 4 of the previous paper.

TABLE II—RATE OF ABSORPTION OF RADIATION

	Solar altitude (h)										
	−5°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
	10^{-3} × *calories per second*										
Shield											
Direct solar (Q_h) ...	447	489	543	575	597	594	543	470	422	405	415
Reflected from below (Q_m)	0	0	37	72	106	137	161	182	198	205	211
Emitted from below (Q_1)	8	8	8	8	8	8	8	8	8	8	8
Total (Q_s)	455	497	588	655	711	739	712	660	628	618	634
Element											
Direct solar (Q_h) ...	6·0	5·3	4·5	4·3	4·1	6·4	7·8	8·1	9·4	11·1	12·2
Reflected from below (Q_m)	0·0	0·0	0·8	1·5	2·3	2·9	3·4	3·8	4·2	4·4	4·6
Emitted from below (Q_1)	0·5	0·5	0·5	0·5	0·5	0·5	0·5	0·5	0·5	0·5	0·5
Total (Q_e)	6·5	5·8	5·8	6·3	6·9	9·8	11·7	12·4	14·1	16·0	17·3

The intensity of solar radiation is taken to be 0·032 cal. cm.$^{-2}$sec.$^{-1}$

The figures for the reflected radiation are for an albedo of 0·40 and those for long-wave radiation emitted from below refer to a surface at 288°K. with the radio-sonde at 220°K.

Revised values of radiation errors.—In re-evaluating the radiation errors the following values of the various factors were adopted:

Absorption factor of temperature element for short waves ...	0·67
Absorption factor of temperature element for long waves ...	0·18
Absorption factor of radiation shield for short waves	0·33
Absorption factor of radiation shield for long waves	0·03
Albedo of earth, cloud and air	0·40
Rate of ascent	6 m./sec.
Half-amplitude of swing of radio-sonde	30°
Intensity of solar radiation at the top of the atmosphere...	0·032 cal./cm.^{2}/sec.

Apart from the albedo these values are the same as were used in the previous paper[1]. The heat-transfer coefficients, q of equation (1), are also the same as in Table 3 of that paper. For the reasons already given the rates of absorption Q differ from the earlier estimates, and the new values given in Table II for the thermometer element and the shield have been used in obtaining the revised values of the radiation errors from Q/q. Since the values of Q assume the intensity of solar radiation to be that at the top of the atmosphere, use has again been made of a diagram provided by Väisälä[4] to allow for depletion of the solar radiation by absorption and scattering before it reaches the radio-sonde. This

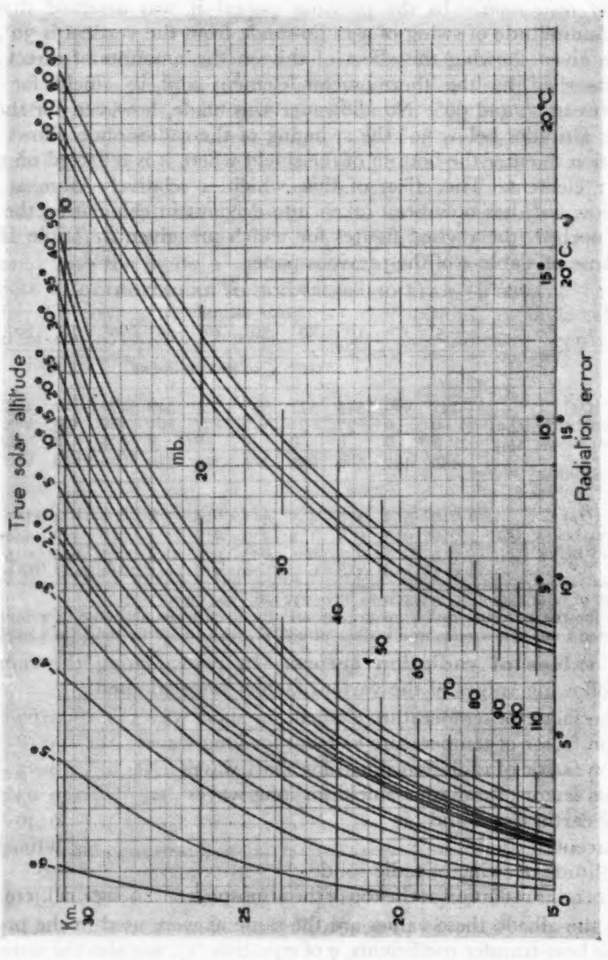

FIG. 1 (a)—RADIATION CORRECTIONS (15–30 KM.)

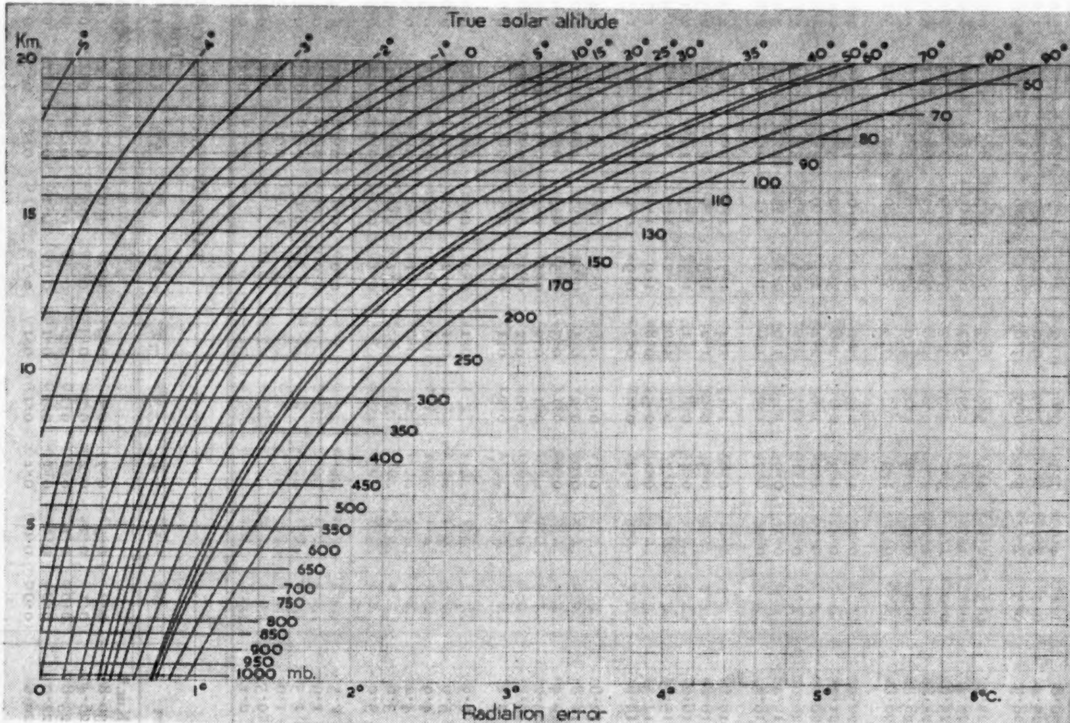

FIG. 1(*b*)—RADIATION CORRECTIONS (BELOW 20 KM.)

TABLE III—RADIATION

Height		−6°	−5°	−4°	−3°	−2°	−1°	0°	5°	10°	15°
										True solar	
mb.	Km.*									*degrees*	*Celsius*
10	30·8	1·1	4·5	7·3	9·6	10·9	11·3	11·7	13·0	14·2	15·0
12	29·4	0·7	3·4	6·0	7·9	9·0	9·4	9·7	10·8	11·6	12·2
14	28·5	0·5	2·8	5·3	6·9	7·8	8·3	8·6	9·6	10·3	10·8
17	27·4	0·3	2·2	4·4	5·8	6·7	7·2	7·5	8·3	8·9	9·4
20	26·4	0·1	1·7	3·7	4·9	5·7	6·2	6·5	7·3	7·8	8·2
23	25·6	0·0	1·4	3·2	4·3	5·2	5·6	5·9	6·6	7·0	7·5
26	24·8	0·0	1·2	2·8	3·8	4·6	5·0	5·3	6·0	6·4	6·7
30	23·8	0·0	0·9	2·3	3·2	4·0	4·3	4·6	5·2	5·6	5·9
35	22·8	...	0·7	1·9	2·7	3·4	3·8	4·0	4·6	4·9	5·2
40	22·0	...	0·5	1·5	2·3	3·0	3·4	3·6	4·1	4·5	4·6
45	21·2	...	0·4	1·3	2·1	2·6	3·0	3·2	3·7	4·0	4·2
50	20·6	...	0·3	1·2	1·8	2·4	2·7	3·0	3·4	3·7	3·8
55	20·0	...	0·2	1·1	1·7	2·2	2·5	2·7	3·1	3·4	3·6
60	19·4	...	0·1	0·9	1·4	1·9	2·2	2·5	2·8	3·1	3·2
70	18·4	...	0·0	0·7	1·2	1·6	1·9	2·1	2·4	2·7	2·8
80	17·6	...	0·0	0·6	1·1	1·4	1·7	1·8	2·2	2·4	2·5
90	16·8	...	...	0·5	0·9	1·2	1·5	1·6	2·0	2·2	2·3
100	16·2	...	...	0·4	0·8	1·1	1·3	1·5	1·8	2·0	2·1
110	15·6	...	...	0·3	0·7	1·0	1·2	1·3	1·6	1·8	1·9
130	14·5	...	...	0·2	0·5	0·8	1·0	1·1	1·4	1·6	1·7
150	13·6	...	...	0·2	0·4	0·7	0·9	0·9	1·3	1·4	1·5
170	12·8	...	...	0·1	0·3	0·6	0·7	0·8	1·1	1·3	1·4
200	11·8	...	...	0·0	0·2	0·5	0·6	0·7	1·0	1·1	1·2
250	10·4	...	...	0·0	0·1	0·3	0·5	0·5	0·8	0·9	1·0
300	9·2	...	...	...	0·1	0·2	0·4	0·4	0·7	0·8	0·9
350	8·1	...	...	...	0·0	0·2	0·3	0·3	0·6	0·7	0·8
400	7·2	...	...	...	0·0	0·1	0·3	0·3	0·5	0·6	0·7
450	6·3	...	...	...	...	0·1	0·2	0·3	0·5	0·6	0·6
500	5·6	...	...	...	...	0·1	0·2	0·2	0·4	0·5	0·6
550	4·9	...	...	...	...	0·0	0·1	0·2	0·4	0·5	0·5
600	4·2	...	...	...	...	0·0	0·1	0·2	0·3	0·4	0·5
650	3·6	...	...	...	...	...	0·1	0·1	0·3	0·4	0·5
700	3·0	...	...	...	...	...	0·1	0·1	0·3	0·4	0·4
750	2·5	...	...	...	...	...	0·0	0·1	0·2	0·3	0·4
800	1·9	...	...	...	...	...	0·0	0·1	0·2	0·3	0·4
850	1·5	...	...	...	...	...	...	0·0	0·2	0·3	0·4
900	1·0	...	...	...	...	...	...	0·0	0·2	0·3	0·3
950	0·5	...	...	...	...	...	...	...	0·1	0·2	0·3
1000	0·1	...	...	...	...	...	...	...	0·1	0·2	0·3

TABLE IV—LAG CORRECTIONS

Height		−6°	−5°	−4°	−3°	−2°	−1°	0°	5°	10°	15°
										True solar	
mb.	Km.*									*degrees*	*Celsius*
10	30·8	0·2	0·5	0·7	0·8	0·9	1·0	1·0	1·1	1·2	1·4
20	26·4	0·1	0·2	0·2	0·3	0·3	0·3	0·3	0·3	0·4	0·4
30	23·8	0·0	0·1	0·1	0·1	0·2	0·2	0·2	0·2	0·2	0·2
40	22·0	0·0	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1
50	20·6	0·0	0·0	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1
60	19·4	0·0	0·0	0·0	0·1	0·1	0·1	0·1	0·1	0·1	0·1
70	18·4	0·0	0·0	0·0	0·0	0·0	0·1	0·1	0·1	0·1	0·1
80	17·6	0·0	0·0	0·0	0·0	0·0	0·0	0·1	0·1	0·1	0·1
90	16·8	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·1
100	16·2	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
110	15·6	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0

* International standard atmosphere.

CORRECTIONS

altitude 20°	25°	30°	35°	40°	50°	60°	70°	80°	90°	Height Km.	mb.
(to be subtracted)											
15·7	16·6	17·7	18·8	20·1	20·7	19·0	19·4	20·1	21·1	30·8	10
12·8	13·5	14·0	14·9	15·9	16·6	16·3	16·8	17·6	18·3	29·4	12
11·4	11·9	12·5	13·2	14·0	14·7	14·6	15·2	15·9	16·6	28·5	14
9·9	10·4	10·8	11·6	12·2	12·8	12·8	13·4	14·1	14·7	27·4	17
8·6	9·1	9·5	10·1	10·8	11·3	11·3	11·6	12·4	13·0	26·4	20
7·8	8·2	8·6	9·2	9·8	10·3	10·4	10·8	11·5	12·0	25·6	23
7·0	7·4	7·8	8·3	8·9	9·3	9·5	9·9	10·5	11·0	24·8	26
6·2	6·5	6·8	7·3	7·9	8·3	8·4	8·7	9·3	9·7	23·8	30
5·4	5·7	5·9	6·5	6·9	7·3	7·5	7·9	8·4	8·8	22·8	35
4·9	5·1	5·3	5·8	6·3	6·6	6·7	7·1	7·6	8·0	22·0	40
4·4	4·6	4·8	5·3	5·7	6·0	6·1	6·6	7·0	7·4	21·2	45
4·0	4·2	4·4	4·9	5·3	5·6	5·6	6·0	6·5	6·9	20·6	50
3·7	3·9	4·0	4·5	4·9	5·2	5·3	5·7	6·1	6·5	20·0	55
3·4	3·5	3·7	4·2	4·5	4·8	4·9	5·2	5·6	6·0	19·4	60
3·0	3·1	3·3	3·7	4·0	4·3	4·4	4·6	5·0	5·4	18·4	70
2·7	2·8	3·0	3·3	3·6	3·9	4·0	4·2	4·6	4·9	17·6	80
2·4	2·5	2·7	3·0	3·3	3·6	3·7	3·9	4·2	4·5	16·8	90
2·2	2·3	2·5	2·8	3·0	3·3	3·4	3·6	3·9	4·2	16·2	100
2·0	2·1	2·3	2·5	2·8	3·1	3·1	3·3	3·6	3·9	15·6	110
1·8	1·9	2·0	2·2	2·5	2·7	2·8	3·0	3·2	3·5	14·5	130
1·6	1·7	1·8	2·0	2·2	2·5	2·5	2·7	3·0	3·2	13·6	150
1·4	1·5	1·6	1·8	2·0	2·3	2·3	2·5	2·7	2·9	12·8	170
1·3	1·4	1·5	1·6	1·8	2·0	2·1	2·3	2·5	2·6	11·8	200
1·1	1·2	1·3	1·4	1·6	1·8	1·8	2·0	2·2	2·3	10·4	250
0·9	1·0	1·1	1·2	1·4	1·6	1·6	1·8	2·0	2·1	9·2	300
0·8	0·9	1·0	1·1	1·3	1·4	1·5	1·6	1·8	1·9	8·1	350
0·8	0·8	0·9	1·0	1·2	1·3	1·4	1·5	1·7	1·8	7·2	400
0·7	0·8	0·8	0·9	1·1	1·2	1·3	1·3	1·5	1·7	6·3	450
0·6	0·7	0·8	0·9	1·0	1·1	1·2	1·3	1·4	1·6	5·6	500
0·6	0·7	0·7	0·8	1·0	1·1	1·1	1·2	1·4	1·5	4·9	550
0·6	0·6	0·7	0·8	0·9	1·0	1·0	1·1	1·3	1·4	4·2	600
0·5	0·6	0·6	0·7	0·8	1·0	1·0	1·0	1·2	1·3	3·6	650
0·5	0·5	0·6	0·7	0·8	0·9	0·9	1·0	1·1	1·2	3·0	700
0·5	0·5	0·6	0·6	0·8	0·9	0·9	0·9	1·1	1·2	2·5	750
0·4	0·5	0·5	0·6	0·7	0·8	0·8	0·9	1·0	1·1	1·9	800
0·4	0·5	0·5	0·6	0·7	0·8	0·8	0·9	1·0	1·1	1·5	850
0·4	0·4	0·5	0·5	0·7	0·8	0·8	0·8	0·9	1·0	1·0	900
0·4	0·4	0·4	0·5	0·6	0·7	0·7	0·8	0·9	1·0	0·5	950
0·4	0·4	0·4	0·5	0·6	0·7	0·7	0·7	0·8	0·9	0·1	1000

TO RADIATION ERRORS

altitude 20°	25°	30°	35°	40°	50°	60°	70°	80°	90°	Height Km.	mb.
(to be subtracted from radiation errors of Fig. 1)											
1·5	1·6	1·7	1·9	2·0	2·0	1·6	1·6	1·5	1·6	30·8	10
0·4	0·4	0·5	0·5	0·5	0·5	0·5	0·5	0·5	0·5	26·4	20
0·2	0·2	0·3	0·3	0·3	0·3	0·3	0·3	0·3	0·3	23·8	30
0·2	0·2	0·2	0·2	0·2	0·2	0·2	0·2	0·2	0·2	22·0	40
0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·2	0·2	20·6	50
0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	19·4	60
0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	18·4	70
0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	17·6	80
0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	16·8	90
0·0	0·0	0·1	0·1	0·1	0·1	0·1	0·1	0·1	0·1	16·2	100
0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·1	0·1	0·1	15·6	110

diagram gives the radiation intensity in terms of true solar altitude, and height as a percentage of the intensity at the top of the atmosphere, and it takes into account refraction of the sun's rays. Different factors should be applied to the direct radiation Q_h at the height of the radio-sonde and to the reflected radiation Q_m at the height of the reflecting surface, which in most cases will be partly cloud and partly the earth's surface. It has not, however, been thought worth while attempting to make this differentiation and the radiation errors have, therefore, been reduced by the factor corresponding to the height of the radio-sonde. The effect of this simplification is generally to increase the errors by about 4 per cent. but it is offset by errors of opposite sign caused by the effect of downward-scattered sky radiation which has not been taken into account.

The radiation errors have been computed in this manner for every 5 Km. height and for true solar altitudes (measured above the horizontal plane) at one-degree intervals from $-5°$ to $0°$C., at five-degree intervals from $0°$ to $40°$C. and at ten-degree intervals from $40°$ to $90°$C. The results are plotted in Figs. 1(*a*) and 1(*b*) and the international standard pressure levels are indicated on the graphs. Table III gives corrections derived from the graphs at these pressure levels. It should be emphasized that since these errors relate only to the first term of the right-hand side of equation (1) they do not take account of the fact that the full radiation effect is reduced by the lag of the thermometer unit in responding to it.

Effect of thermometer lag.—The error arising from the lag of the thermometer unit is represented by the last term of equation (1). The rate of change of indicated temperature, dS/dt, on which it depends may arise partly from the change due to the radiational heating, if the sounding is in daylight, and partly from the change of air temperature with height. Since, in general, kdS/dt is small compared with the full radiation error Q/q, equation (1) approximates to

$$S - T = R - k\left(\frac{dR}{dt} + \frac{dT}{dt}\right), \qquad \ldots\ldots (2)$$

where R is substituted for Q/q. The term kdR/dt is the lag in the response to radiational heating whereas kdT/dt is the lag associated with the change in air temperature.

Since kdR/dt can be written as $kVdR/dz$, where z is the height and V the rate of ascent, it can be readily evaluated from the slopes of the curves of Fig. 1 and the values of k appropriate to the standard rate of ascent of 6 m./sec. and the height. The values of k given in the previous paper have been used; they are as follows:

Height (Km.) ...	0	5	10	15	20	25	30
k (sec.)	7·4	9·5	12·9	20	33	54	97

The values so obtained for the lag corrections to the radiation errors are given in Table IV. They are less than 0·1°C. at levels below 110 mb., but at 10 mb. they are large enough to reduce the radiation errors by about 10 per cent.

The last term in equation (2), which may be written as $kVdT/dz$, represents the ordinary lag error of a thermometer following a uniform change of air temperature. Table V gives corrections for this error when the change results from the radio-sonde ascending at 6 m./sec. in temperature gradients of $-6°$C./Km. in the troposphere and 1°C./Km. in the stratosphere. Corrections for other gradients are in proportion to their magnitude. These lag corrections, unlike those for the radiation errors, apply by night as well as by day.

It should be noted from equation (1) that combined lag corrections for the radiation effect and for changes in air temperature at any part of a sounding can be evaluated as the product of the lag coefficient and the rate of change of indicated temperature. It is preferable to adopt this procedure for correcting observations in the stratosphere, but for the troposphere, in which the lag in radiation error is negligible and in which a lapse rate of 6°C./Km. is sufficiently representative of nearly all conditions, the use of Table V(*a*) is to be preferred.

TABLE V—LAG CORRECTIONS FOR CHANGES IN TRUE AIR TEMPERATURE WITH HEIGHT

Height	(*a*) Troposphere Correction for assumed* lapse rate of 6°C./Km. at a rate of ascent of 6 m./sec.	Height	(*b*) Stratosphere Correction for assumed* inversion of 1°C./Km.
mb.	°C.	mb.	°C.
95–109	−0·8	10	0·7
110–139	−0·7	20	0·4
140–189	−0·6	30	0·3
190–289	−0·5	40–80	0·2
290–509	−0·4	90–200	0·1
510–1050	−0·3		

* Corrections for other temperature gradients are in proportion to their magnitude. The sign of the corrections is negative for temperature lapse and positive for inversion.

Lag errors at discontinuities.—The errors, due to lag, in determining the height and temperature at a discontinuity can be evaluated in the following way. Let the true air temperature at a discontinuity where there is a sudden change of temperature gradient dT/dz from A to B be T_d, so that air temperatures below and above the discontinuity are given by $(T_d + Az)$ and $(T_d + Bz)$, where z is height measured from the discontinuity and is therefore negative below, and A and B are negative for lapses. Then, in accordance with the last section, the temperature indicated by the radio-sonde at the true height of the discontinuity is $(T_d - kVA)$. Above that height it is governed by the relation

$$kV\frac{dS}{dz} = T_d + Bz - S, \qquad \ldots\ldots (3)$$

the solution of which is

$$S = T_d + Bz - BkV + kV\,(B - A)\,e^{-z/kV}. \qquad \ldots\ldots (4)$$

When, as in (*a*) of Fig. 2, there is a change of sign of temperature gradient at the discontinuity, the latter can best be recognized in the graph of the observed temperatures as the point, at z_1 say, where dS/dz is zero. Differentiation of equation (4) then shows that the error in the indicated height is given by

$$z_1 = kV \log_e (1 - A/B). \qquad \ldots\ldots (5)$$

At the indicated height the radio-sonde temperature S_1 and the air temperature are the same, i.e. $T_d + Bz_1$. The difference, Bz_1, between this temperature and the air temperature T_d at the true height of the discontinuity is, therefore, $BkV \log_e (1 - A/B)$.

For a tropopause at 10 Km. at which, for example, there is a change from a lapse rate of 6°C./Km. to an inversion of 1°C./Km. the height error for $V = 6$ m./sec. and $k = 13$ sec. is + 150 m. and the temperature error is + 0·15°C. For a sharper tropopause with an inversion of 6°C./Km. the corresponding errors are + 54 m. and + 0·3°C. At inversions near the ground, where k is about 7 sec., the errors are roughly half these values.

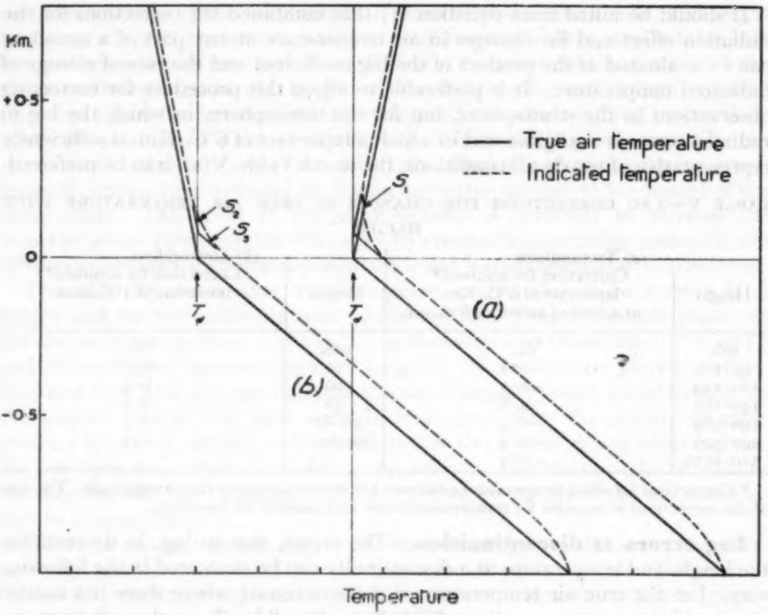

FIG. 2—ERRORS DUE TO LAG, IN HEIGHT AND TEMPERATURE OF A DISCONTINUITY

At a discontinuity, such as that illustrated in (*b*) of Fig. 2, where there is no change in sign of the temperature gradient the fact that dS/dz does not pass through zero, together with the smoothing effect of the lag, makes it difficult to determine precisely the observed height of the discontinuity. It could be specified in terms of a particular value, D, of dS/dz, such as a lapse rate of 2°C./Km. In that case by differentiation of equation (4)

$$D = B - (B - A)\, e^{-z/kV}, \qquad \ldots\ldots \quad (6)$$

giving the height error

$$z_1 = kV \log_e (A - B)/(D - B). \qquad \ldots\ldots \quad (7)$$

For a tropopause at 10 Km. separating lapse rates of 6° and 1°C./Km. this amounts to + 125 m. and the temperature, S_2 in Fig. 2(*b*), exceeds the true tropopause temperature by + 0·03°C. Such a discontinuity, however, is probably more readily recognized in the observations as the point S_3 where the gradient is the mean of A and B. In this case equation (6) shows the height error to be $kV \log_e 2$, which for the above example amounts to + 54 m., the temperature error being + 0·22°C.

It follows from the expressions for the straight portions of the graphs o indicated temperatures in Fig. 2, where the exponential changes have become negligible, that they intersect at the true temperature of the discontinuity and at a height kV above it. It is doubtful, however, whether in practice the temperature gradient remains constant long enough to make this procedure practicable.

The temperature and height errors at discontinuities, though systematic, are not very important in individual cases since with radio-sonde readings at intervals of about 150 m. the discontinuities can hardly be determined to a higher accuracy than this.

Application of corrections to Meteorological Office observations.—In 1953 the World Meteorological Organization recommended that all radio-sonde observations should be corrected for radiation errors on the basis of the best information available. In accordance with this recommendation the radiation corrections of Table III, adjusted if necessary for departures from the standard rate of ascent, are being applied to upper air temperatures observed at Meteorological Office radio-sonde stations at home from February 1 and overseas from March 1, 1956. For climatological purposes the observations made in January will also be corrected. In addition the lag corrections of Table V(*a*) are being applied as standard corrections to all observations in the troposphere. For observations in the stratosphere corrections derived from the rate of change of indicated temperature and the appropriate lag coefficient are applied when a temperature gradient departing from isothermal is maintained over a sufficient depth to render the corrections significant in the computation of the heights of pressure levels.

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METEOROLOGICAL OFFICE PRACTICE FOR THE APPLICATION OF RADIATION AND LAG CORRECTIONS TO TEMPERATURES MEASURED BY RADIO-SONDE MK IIB

By C. L. HAWSON, B.A.

Methods have been devised by Scrase[1,2] for evaluating the temperature errors of the Meteorological Office radio-sonde Mk IIB arising from the effects of solar radiation and of thermometer lag. Corrections for these errors are now being applied at all Meteorological Office radio-sonde stations. For synoptic messages the corrections were introduced from February 1, 1956 at home stations and in ocean weather ships, and from March 1, 1956 at Meteorological Office stations overseas. For climatological purposes the corrections were applied from January 1, 1956 at all stations. The purpose of this note is to outline the methods adopted for applying the corrections on a routine basis. These methods, which have been evolved by the staff of the Upper Air Observations Branch of the Meteorological Office, effect a balance between the conflicting requirements for a minimum increase of computation time, and for as high an accuracy as practicable in the determination of the heights of the standard pressure surfaces.

Basic radio-sonde observations.—In the Meteorological Office radio-sonde system the frequency of an audio modulation of a radio carrier is measured and plotted against time. The frequency of this audio modulation is controlled successively by the pressure, temperature, and humidity elements of the airborne transmitter. Thus at the ground station the initial record

consists of a series of observations of frequency plotted against time, which fall naturally into three separate curves corresponding to the variations of the three atmospheric parameters. Time is recorded to the nearest 3 sec. and frequency to the nearest ½ c./sec., corresponding in the case of temperature to approximately ¼°C. The combined lag and radiation corrections, determined for each computed temperature observation as described below, are rounded off to the nearest ¼°C. before they are applied.

Radiation corrections.—Before the ascent the times at which the sun will pass through certain chosen values of true solar altitude at the particular station, during the flight, are derived by means of the tables given in "Sight reduction tables for air navigation"[3] and *The abridged nautical almanac*[4]. The values of true solar altitude chosen for this purpose are those intermediate to the values given in the heading of Table III of Dr. Scrase's paper on pp. 70–1. A series of time intervals during each of which a particular column of Table III is applicable is thus obtained, and can be readily related to the time used in the frequency/time plot, i.e. to the time of any part of the ascent. No adjustment of the solar altitude to allow for the down-wind drift of the radio-sonde during the flight is attempted. This drift can readily introduce solar-altitude errors of the order of ½° but the corresponding radiation errors are less than 0·2°C., except in a few instances, principally when small negative values of solar altitude are experienced at altitudes above about the 100-mb. level.

The radiation correction for each computed temperature observation is initially determined from Table III. The times at which the temperature observations are made are used to determine both the appropriate pressure lines and the appropriate solar-altitude columns of Table III. The values of the radiation corrections are read directly without interpolation. When the departure of the actual rate of ascent from that assumed in computing the table would introduce a change of more than 0·2°C. in the value of the radiation correction, each correction is adjusted using the formula given by Scrase. For this purpose rates of ascent determined by measuring the times taken to ascend through 3-Km. layers are normally employed. The methods of selecting the 3-Km. layers and applying the adjustment are both graphical, but introduce no significant inaccuracy beyond that inherent in the basic pressure observations[5].

Lag corrections.—Lag corrections depend directly on the lag coefficient of the thermometer and upon the rate of change of temperature experienced with time. The former increases fivefold as the pressure decreases from 1000 to 50 mb. The latter is unique for each sounding, changing frequently in magnitude and less frequently in sign. It is indicated, to the first order by the rate of change of temperature frequency with time. To apply lag corrections based upon all the detailed rates of change of temperature observed on each individual sounding would involve a considerable increase in the time required to compute the sounding. Therefore, in order to expedite computation, the sounding is divided into broad sections or régimes, each naturally defined by the general slope of the observed temperature-frequency/time plot, and the mean value of this slope over each section is taken as a common value for all temperature observations in the section.

The first section chosen normally extends from the ground to the first tropopause. In this régime the lag coefficients are so small that a standard lapse of

6°C./Km. coupled with a standard rate of ascent of 6 m./sec. is assumed instead of the observed lapse. The consequent inaccuracy introduced into the lag corrections, when meaned over the section, rarely exceeds 0·1°C. In this first régime, therefore, the standard lag corrections of the appropriate pressure ranges of Table V(*a*) on p. 73 are used for each temperature observation, no adjustment for the observed lapse rate being attempted. The extent of the first section is occasionally varied as to its upper limit, either when the first tropopause is not readily apparent, or has not been encountered up to a height corresponding to 95 mb.

Sections subsequent to the first are normally in the stratosphere. Here the lag coefficients are larger than in the first section, and although the overall lapse rate approximates to isothermal, local departures occur which can be maintained over a sufficient depth to render the lag correction significant in the computation of the heights of the standard pressure levels. In each of these subsequent sections therefore, the observed mean slope of the temperature-frequency/time plot and the appropriate pressure value are used to determine the lag correction for each temperature observation. The actual determination is carried out graphically, assuming a constant factor for the conversion of temperature-frequency changes to degrees Celsius. Actual values of this factor have a standard deviation of approximately 11 per cent. of the assumed constant value, and the errors involved in the assumption are directly reflected in the derived corrections. Thus the lag corrections employed embody an error with a standard deviation of approximately 11 per cent. of the value of the correction. In practice this error rarely reaches 0·2°C. except in very shallow layers and introduces inaccuracies of the order of 1 m. in the computation of the heights of the standard pressure surfaces above the first tropopause.

The routine methods of application of the lag corrections, although rarely introducing significant inaccuracies into the computed heights of the standard pressure surfaces, can introduce appreciable error in the temperature at individual levels, e.g. in a tropospheric inversion. In the troposphere these errors in any particular case can be assessed by the user if required. The lapse rates as reported are representative of the true rates of change of temperature to the first order and corrections appropriate to these lapse rates can be derived from Table V(*a*) on p. 73 by applying the ratio

$$\frac{\text{actual change}}{\text{standard assumed change (6°C./Km.)}}$$

and choosing the appropriate sign. These can then be compared with the standard corrections. For example at 400 mb., for a temperature observed in a region of lapse rate 7°C./Km., the appropriate correction is −0·5°C., whilst for a temperature observed in an inversion of 6°C./Km. the appropriate correction is +0·4°C. The standard correction is −0·4°C. Thus the temperature corrected by the routine method is 0·1°C. too warm or 0·8°C. too cold respectively. In the stratosphere similar errors occur when the rate of change of temperature departs from the mean employed for the particular section, these errors however cannot be readily determined without reference to the original computation.

The temperature errors at individual levels arising from the simplified application of lag corrections are normally unimportant[6], and although they could be eliminated at the radio-sonde stations to do so would incur a delay to the reported message quite disproportionate to the gain in accuracy.

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TRANS-ANTARCTIC EXPEDITION, 1955–58

By R. H. A. STEWART, B.Sc.(Tech.)

The aim of this expedition, under the leadership of Dr. V. E. Fuchs, is to cross the Antarctic continent from the Weddell Sea to the Ross Sea and to carry out a full programme of geophysical research, including meteorology and glaciology. Articles by Dr. Fuchs and by the leader of the New Zealand Party, Sir Edmund Hillary, describing the expedition are appearing exclusively in *The Times.*

The main base was set up at Vahsel Bay (78°S. 35°W.) in January 1956, and a full meteorological programme will start as soon as the base is established. Surface observations will be made at all the synoptic hours and more frequently when air operations are in progress. It is expected that the observations will be transmitted to Stanley, Falkland Isles, for inclusion in collective broadcasts, and possibly to Cape Town also. The base will have a radio-sonde station and a daily ascent will be attempted. This will yield measurements of temperature, pressure and humidity up to perhaps 10 miles. Upper winds will be measured by pilot balloon whenever conditions are favourable. In addition a programme of radiation and glaciological measurements has been planned. The radiation work will consist of obtaining continuous records, by a bimetallic recorder, of short-wave radiation received on a horizontal surface together with the measurement, on selected occasions, of the vertical flux of total short-wave and long-wave radiation.

In March 1957, an additional station will be established 300 miles inland from Vahsel Bay at an altitude of about 8,000 ft. This will be manned until November 1957, and during this time synoptic observations and possibly pilot-balloon ascents will be carried out.

Most of the equipment will be of standard Meteorological Office pattern, but the low temperatures likely to be encountered have raised a number of problems of instrument design and operation, many of which will only be solved by experience. Screen temperatures down to −80°F. may be experienced and low-range thermometers, including mercury/thallium maximum thermometers, will be used. Wind-driven snow frequently makes it almost impossible to maintain proper ventilation through a Stevenson screen, and although many devices have been tried, a satisfactory answer has not yet been found. The expedition will be testing a new type of screen designed by the Meteorological Office in yet a further attempt to solve this problem.

Hydrogen generation for balloons is another question which has been given much consideration. Hydrogen in cylinders cannot be taken as the amount of useless weight is too great. Some types of chemical generator have also been

ruled out owing to the volume of water that they require. Water in its liquid form is a rare and valuable item in the Antarctic, and can only be produced by the expenditure of much valuable fuel. It is intended to try both low-pressure and high-pressure generators, using ferro-silicon and caustic soda, and requiring not more than five gallons of water for each charge.

Weather conditions in winter are frequently such as to make outdoor observation both difficult and dangerous. With this in mind distant-reading instruments for wind, temperature and humidity are being provided at the coastal station, and for wind and temperature at the inland station.

The expedition will initially include three meteorologists, one former member of the staff of the Meteorological Office (Mr. R. H. A. Stewart), one South African meteorologist (Mr. J. J. Le Grange), and one present member of the staff of the Meteorological Office (Mr. P. H. Jeffries).

It is hoped that at least one meteorologist will be a member of the party which, between November 1957 and March 1958, will attempt the continental crossing.

MINIMUM TEMPERATURES AND TOPOGRAPHY IN A HEREFORDSHIRE VALLEY

By E. N. LAWRENCE, B.Sc.

Introduction.—One of the chief methods of minimizing frost damage to fruit crops is by means of careful siting of orchards. In April and May 1954 an attempt to assess the frost risk[1,2] of a site at Long Orchard, which is about half a mile to the south-south-west of Much Birch, near Hereford (see photographs in the centre of this magazine) has produced some interesting microclimatological data relating minimum temperature to topography, mainly surface contours.

Data.—Eight minimum thermometers (of the sheathed spirit type) with white painted shields, attached to vertical posts at a height of 4 ft. above the ground, were distributed as shown in Fig. 1. Four of these thermometers (numbers 5, 6, 7 and 8) were placed at height intervals of 10 ft. along a "trough" line, i.e. in a valley at points of approximately maximum curvature of contours, while the other four thermometers (numbers 1, 2, 3 and 4) were placed along a roughly parallel line on the side of the valley, where the contours were approximately straight, and so that thermometers 2, 3 and 4 were at the same heights as thermometers 8, 7 and 6 respectively.

All readings quoted are actual readings, but to compare with screen minimum temperatures it is estimated that 0·9°F. must be added to the readings of weeks 1–4 (April 2–29) and 0·8°F. to the readings of weeks 5–8 (April 30–May 27) to allow for instrumental differences. The field under consideration was sown with crops as shown in Fig. 1. The progress of crop growth is given in Table I.

During the month of May the change in height of the crop and percentage ground cover made analysis difficult, but during April the percentage ground cover, even at the end of the month, did not exceed 15 per cent. Thus the analysis refers primarily to April readings. April 1954 was an anticyclonic month. The average pressure (April 2–29) was about 1024 mb. as compared with a long-term mean of 1013–1014 mb., and the rainfall in the area was only

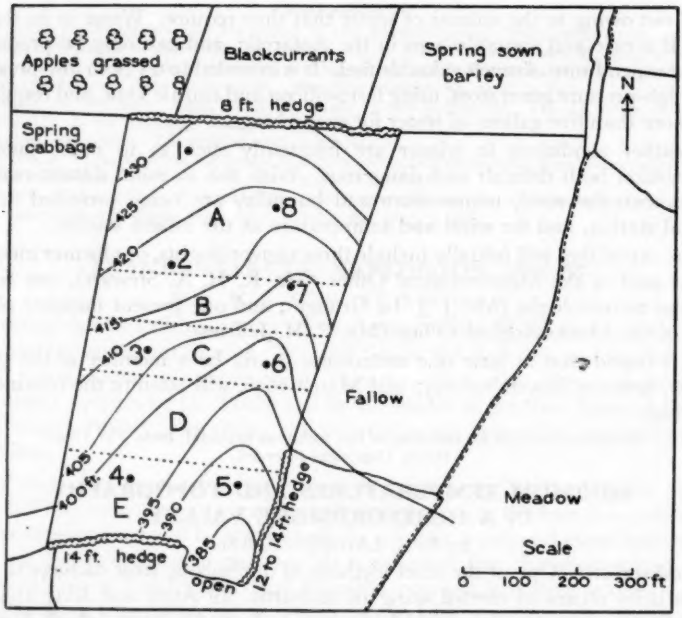

FIG. 1—CONTOURS, LAYOUT AND SURROUNDINGS OF EXPERIMENTAL FIELD

A First sowing peas B Third sowing peas
C Second sowing peas D Potatoes
E Fourth sowing peas

The positions of the thermometers are indicated by numbers

0·2 in., so that night minimum temperatures below average might have been expected. The differences between the 1954 value of the average minimum temperature and the long-term average, together with the corresponding "anomalies" in the weekly spread coefficient (i.e. average weekly minimum temperature minus extreme weekly minimum temperature), are given in Table II.

TABLE I—STATE OF CROP GROWTH ON THE EXPERIMENTAL FIELD

	1st sowing peas Thermometers 1, 2, 8		3rd sowing peas Thermometer 7		2nd sowing peas Thermometers 3, 6		4th sowing peas Thermometers 4, 5		Potatoes	
	Height of crop	Ground cover	Height of crop	Ground cover	Height of crop	Ground cover	Height of crop	Ground cover	Height of crop	Ground cover
	in.	%	in.	%	in.	%	in.	%	in.	%
April 2	1	Negligible	Bare soil		Bare soil		Bare soil		Bare soil	
April 9	2	Negligible	Bare soil		Bare soil		Bare soil		Bare soil	
May 2	8	15	1	Negligible	4	5	1	Negligible	Just appearing	Negligible
May 8			Peas (2–9 in.)						Negligible	Negligible
May 22	12	75	4	10	12	50	9	40	4–6	7
May 31	18	90	5	30	18	70	15	60	6–18	13

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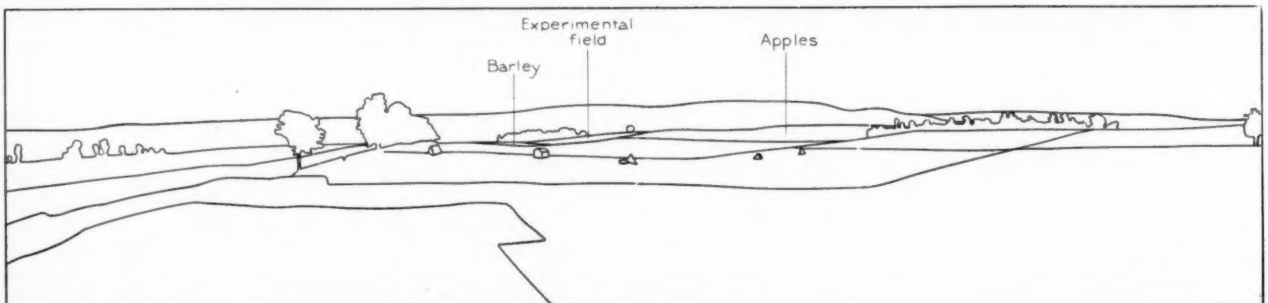


POSITION OF EXPERIMENTAL FIELD, LONG ORCHARD, MUCH BIRCH

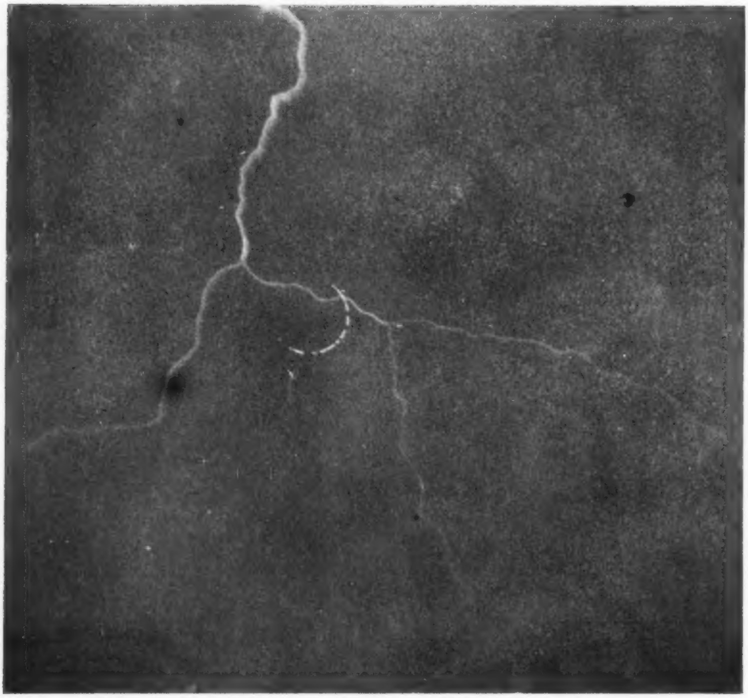
Looking south (see p. 79)

FROST EXPERIMENTAL FIELD, LONG ORCHARD, MUCH BIRCH

North-east corner looking south (see p. 79)

FROST EXPERIMENTAL FIELD, LONG ORCHARD, MUCH BIRCH
South-east corner looking north-west (see p. 79)

To face p. 81]



LIGHTNING RECORDED BY NIGHT-SKY CAMERA

This photograph of a lightning flash was recorded on the film of the night-sky camera at Stornoway on the night of December 2–3 during normal operation. The trace made by the Pole Star may also be seen in the picture, indicating that the cloud during the night was very broken. Frequent thunderstorms were reported from Stornoway and other stations in the Hebrides that evening and throughout the night the photograph was taken.

It is extremely rare to find a flash so recorded. Night-sky cameras have been in operation more or less continuously since 1947 or 1948 at about a dozen stations in different parts of the country, but the only other known record of such a flash occurred at Porton, Wiltshire, during the development of the prototype night-sky camera in the late 1920's.

R. E. BOOTH

TABLE II—ANOMALIES OF MEAN TEMPERATURE AND SPREAD COEFFICIENT IN APRIL 1954

	1954 average minus long-term average Minimum temperature	Weekly spread coefficient
	degrees Fahrenheit	
Ross-on-Wye	−2·1	−0·9
Parkend	−3·0	−1·3
Malvern	−2·2	−0·1
Droitwich	−3·8	−1·5
Stratford-on-Avon	−4·1	−0·9

To assess the frost liability of the site at Long Orchard, these values were plotted on a map in order to obtain a measure of the April 1954 anomaly at Long Orchard, there being no single "standard" meteorological site in the same climatological régime as the site being assessed. This measure was used to "adjust" the Long Orchard observations, which were then smoothed (as described in an earlier paper[2]) to obtain the long-term average minimum temperature and long-term average spread coefficient for Long Orchard, and hence the frost frequency[2].

Results.—The temperature measurements are shown in Table III.

TABLE III—AVERAGE WEEKLY AND EXTREME WEEKLY MINIMUM TEMPERATURES

	Minimum temperature	Thermometers 1 (427 ft.)	2 (417 ft.)	3 (407 ft.)	4 (397 ft.)	5 (387 ft.)	6 (397 ft.)	7 (407 ft.)	8 (417 ft.)
1954		*degrees Fahrenheit*							
Week 1	Average ...	36·8	37·7	37·3	37·5	36·5	37·6	37·6	36·9
Apr. 2–8 ...	Extreme ...	30·8	32·0	31·8	30·1	28·2	30·4	30·5	30·4
Week 2	Average ...	35·0	36·8	36·9	35·9	34·8	35·1	35·6	34·6
Apr. 9–15 ...	Extreme ...	30·8	33·0	32·8	33·1	30·2	29·9	30·5	29·4
Week 3	Average ...	35·8	36·6	36·8	36·6	35·4	35·6	36·2	35·8
Apr. 16–22 ...	Extreme ...	31·8	32·5	32·8	32·1	30·2	31·4	32·5	31·4
Week 4	Average ...	35·2	35·9	35·8	35·8	34·8	34·7	35·3	35·1
Apr. 23–29 ...	Extreme ...	29·3	30·0	30·3	30·1	29·7	28·9	29·0	29·4
Week 5	Average ...	37·9	38·6	38·7	39·0	37·8	37·2	38·9	37·8
Apr. 30–May 6	Extreme ...	32·8	33·0	32·8	33·1	32·2	31·4	32·0	31·9
Week 6	Average ...	39·8	41·0	42·0	41·3	38·7	38·5	39·7	39·5
May 7–13	Extreme ...	33·3	35·0	34·8	34·6	32·2	31·9	33·0	32·4
Week 7	Average ...	42·2	42·3	42·9	43·1	42·3	40·8	42·5	42·4
May 14–20 ...	Extreme ...	35·8	36·0	36·3	36·6	36·2	34·4	36·0	35·9
Week 8	Average ...	44·5	45·3	45·2	45·4	44·1	42·5	44·1	44·3
May 21–27 ...	Extreme ...	40·3	42·5	42·9	43·1	40·2	38·4	40·0	39·9
Week 1–4	Average ...	35·7	36·7	36·7	36·5	35·4	35·7	36·2	35·6
Apr. 2–29 ...	Extreme ...	30·7	31·9	31·9	31·3	29·6	30·1	30·6	30·1
Week 5–8	Average ...	41·1	41·8	42·2	42·2	40·7	39·7	41·3	41·0
Apr. 30–May 27	Extreme ...	35·5	36·6	36·7	36·9	35·2	34·0	35·3	35·0

Consider the period April 2–29 (i.e. weeks 1–4) and the three pairs of thermometers:—

Thermometers 2 and 8 at 417 ft., both on first sowing of peas.

Thermometers 3 and 7 at 407 ft., on the second and third sowing of peas, respectively.

Thermometers 4 and 6 at 397 ft., on the fourth and second sowing of peas, respectively.

The three "bank" sites at 2, 3 and 4 were warmer than the corresponding "trough" sites at 8, 7 and 6 respectively. The average excess temperature was 0·8°F., but 1·1°F. for the anticyclonic nights of April 7, 8, 9, 10, 14, 16, 21, 24, 25, 27 and 29, 1954. The three "trough" sites had greater weekly spread coefficients (weekly average minus weekly extreme) than the corresponding "bank" sites. The average excess temperature was 0·6°F.

These results suggest that points on concave contours have lower average minimum temperatures and higher average spread coefficients (and hence are frostier) than points on straight contours, other things being equal. A similar result at 40 cm. above the ground was obtained by Geslin[3], who examined the period April 12–20 (which did not include any typical radiation nights) and the frosty night of April 29–30, 1951, in Champagne vineyards. He found that broadly speaking the isopleths of minimum temperature followed the contours, but that for places at the same level the minima were higher on "crest" lines than on "trough" lines. This phenomenon may be explained by the thicker or deeper cold air flow in the trough due to convergence and canalization of the katabatic flow. If the flow were generally a shallow one, convergence and canalization could lead to stronger wind velocities in the trough than on the bank[4], and hence to greater mixing of the shallow cold-air layer with that at thermometer level.

It may be noted here that the generally steeper and more southerly and sheltered aspect of the thermometers 8, 7 and 6 would normally produce a higher day temperature. Furthermore, the smaller night wind (on radiation nights) over thermometers 2, 3 and 4, would encourage inversion conditions. Both these factors would tend to give lower minimum temperatures on the bank sites, which is contrary to observation.

The thermometer at point 1 appears to give a reading lower than might have been expected from considerations of height and shape of contour. This may be due to the proximity of the upslope field of blackcurrants (height 3 ft. 6 in. to 3 ft. 9 in., cover 35 per cent.) which would tend to form a radiating surface immediately upslope at about the same height as the thermometers (i.e. 4 ft.). The grassed bush apple (see Fig. 1) may have had a similar effect, possibly emphasized by the grass. Also, both these crops may have encouraged inversion conditions (low minimum temperatures) by acting as an obstruction to wind. All three thermometers (1, 2 and 8) on the first sowing appear to give temperatures a little lower than might have been expected from considerations of height. This could be due to the slightly higher radiating surface and its slightly greater frictional reduction of wind.

Ignoring the three thermometers on the first sowing, the remaining ones give an average-minimum-temperature increase with height of 1°F./30 ft. and an average-weekly-spread-coefficient decrease with height of about 1°F./50 ft. For the previously mentioned 11 radiation nights, the rate of increase in average minimum temperature with height was 1°F./20 ft. On a particular night, the rate may vary considerably from point to point, and from his results Geslin suggested that the accumulation of cold air in frost hollows tends to equalize temperatures below the level of the surface of the "lake" of cold air.

The data obtained by Geslin were supplemented by observations of damage to vines, and he found that for a given night minimum temperature, the

damage was less on hills than in valleys. This, he explains, could be due to the longer duration of the minimum temperature in valleys. Another important contributing factor could be the greater speed of air flow in the valleys during radiation conditions.

Acknowledgement.—I am indebted to the County Horticultural Staff of the National Agricultural Advisory Service at Hereford for their help in arranging the experiment, and to the grower, Mr. Acheson of Much Birch, Hereford, without whose observations the work would not have been possible.

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METEOROLOGICAL OFFICE DISCUSSION

Three-front model

The Discussion on Monday, December 19, 1955, held at the Royal Society of Arts, was opened by Mr. B. W. Boville of the Canadian Central Analysis Office. He described the procedure at that Office and in particular the three-front model that had been developed there.

When the Central Analysis Office was established in 1951 six meteorologists, all with 10–15 years of synoptic experience in various parts of Canada, were assigned to work out an organization on both the theoretical and administrative side. This analysis and short-range prognosis centre was to meet the requirements of the whole country. To eliminate duplication of work transmission was to be by facsimile. An extended-period forecast centre was to be developed simultaneously.

The status of surface fronts was rather chaotic; coded analyses exchanged among major forecast centres in Canada and abroad indicated, in many cases, areas of agreement arising by chance rather than by science. It was clear that an approach based on detailed study of surface hourly and synoptic reports would not solve the problem.

Differential analysis was reasonable up to 500 mb. although investigation of some forecast failures over the North Atlantic showed that this method had failed to preserve essential details of the flow required for synoptic developments. Although 300-mb. and 200-mb. charts were being drawn it was clear that knowledge of the jet-stream structure and behaviour was rather superficial.

In some parts of the meteorological world fronts were tending to be regarded as transient surface phenomena largely dependent on frictional convergence. In contrast jet streams, which are associated with strong baroclinity and support the idea of three-dimensional fronts, were gaining prominence. It was necessary to devise a new system of analysis which could be applied uniformly by a group and would be acceptable to forecasting centres spread out over a distance of 3,000 nautical miles.

The experiment covered a period of about two years before the method became operational. All standard charts up to 300 mb. were analysed for an

area stretching from Japan to eastern Europe; tephigrams were plotted for all temperature ascents (about 150 stations) and hodographs drawn for upper wind data (about 99 stations) for the area from the central Pacific to the central Atlantic. A number of detailed cross-sections from the surface to 100 mb. were also constructed each day.

Frontal-contour analysis seemed the most promising approach. Initially wet-bulb potential temperature and saturated wet-bulb temperature were plotted at all significant first-order discontinuities in vertical temperature and wind shear. Wet-bulb potential temperature was used as the major identifier but density was the fundamental parameter of discontinuity. It became clear that the three-dimensional picture of the fronts provided a sound relationship between surface fronts, upper westerlies and jet streams. Surface analyses became to a large extent unique with excellent continuity. Jet-stream analysis could be extended into areas of sparse data.

It became evident that there were three major frontal zones, at least in the two-thirds of the hemisphere covered by the analysis. These were named:

Polar front, separating tropical-maritime air and polar-maritime air (mT/mP).

Maritime front, separating polar-maritime air and arctic-maritime air (mP/mA).

Arctic front, separating arctic-maritime air and arctic-continental air (mA/cA).

Several other charts were tested. Charts of particular wet-bulb potential temperature proved difficult to define by a single surface and history, and continuity were not satisfactory. Charts of three-dimensional zones of maximum wind shear were quite interesting in relation to fronts but were somewhat discontinuous and transitory. Tropopause contour charts verified the general relationship with broad air masses and fronts.

Only the three-dimensional "density" discontinuity fronts had the desirable properties of continuity in space and time. They are of course subject to frontolysis and frontogenesis at all levels, but usually on a broad enough scale to handle synoptically.

A method of charting frontal intensity has not yet been found because of the difficulty of varying slope. Even if the gradient of temperature normal to the front remains constant the horizontal and vertical gradients of temperature can change relatively as the slope of the front changes. Both horizontal and vertical temperature gradients can, of course, decrease together with the front eventually disappearing.

It was found in the experiment that occlusions rarely occurred. The major feature was a trough of warm air aloft which had been given the name "trowal". The trowal moved with the wind field and was significant for both weather and development.

Mapping of jet streams by drawing isotachs at the level of the maximum wind was tried. This proved interesting but was difficult to interpret. The major features and details of the jet streams and maxima could be charted by isotach analysis at 300 mb. One method, very useful experimentally, was to grid shear isotachs on to isotachs at 500 mb. on the assumption of constant wind direction. The jet-stream analysis proved very satisfactory; a jet-stream maximum could be traced from an area of sparse data to an area of good data (Canada) and into an area of abundant data (central United States). Even in

such a dense network of wind observations as that over the United States the maximum wind strength can miss the observing stations for thousands of miles; however, the sloping baroclinic zone will intersect the stations.

Mr. Boville illustrated the Canadian technique with two series of charts and diagrams. The first series* showed how a cross-section can be drawn and the winds calculated using the thermal wind equation

$$\frac{\partial V_H}{\partial z} = -\frac{g}{fT}\frac{\partial T}{\partial n}$$

where V_H is the horizontal wind component, f the Coriolis parameter, T the temperature, z the height and $\partial T/\partial n$ the temperature gradient perpendicular to the wind component. Cross-sections were drawn approximately normal to the wind flow, and two fronts were clearly marked from the tephigrams. The first cross-section showed the wind field as calculated up to the 50-mb. level using all the temperature data and only the wind observations from the ground to 700 mb. The second cross-section was drawn from the actual wind observations. The similarity between the wind fields was striking, both cross-sections showing a jet stream of more than 140 kt. just below the tropopause and a possible secondary jet stream at 100 mb. well above the tropopause. The main jet stream had an observed wind speed of more than 160 kt. Further discrepancies between the two wind fields could possibly be explained by neglect of anticyclonic curvature of the stream-lines in the calculated wind field and partly by the depth over which the observed winds are averaged to obtain the wind at a specific level.

The second series† showed the situation over Canada, the United States and Greenland on January 11 and 12, 1954, and illustrated the different features shown by the surface synoptic map, the frontal-contour chart, and the 500-mb. and 300-mb. contour charts. The frontal contour chart shows where each of the three fronts cuts the 850-mb., 700-mb. and 500-mb. surfaces. Trowals were marked along some of the isobaric troughs on the surface chart; they appeared as kinks or waves on the frontal contour chart. On these two days the western coast was affected by the arctic and maritime fronts and also—as shown by the frontal-contour chart alone—by the polar front at higher levels. Except in the extreme south and along the east coast the maritime front did not reach the land surface on the 11th; the frontal-contour chart showed that it was present aloft as far north as 70°N. but was occluded out in these latitudes during the day. The arctic front extended from northern British Columbia to the Middle West of North America eventually being gathered up with the maritime and polar fronts into one very strong front over the eastern states. There was marked confluence over this strong front which formed a typical deepening polar-front depression during the 11th (the central pressure fell from 1004 to 976 mb. in 24 hr.).

Isotachs were drawn every 20 kt. above 60 kt. on the 300-mb. charts and jet-stream positions were clearly visible. On the 11th there were two jet streams of 110–130 kt. (associated with the maritime front) meandering across the country to combine into one jet stream of 200 kt. (associated with the combined front over the eastern States). On the 12th the jet stream associated

* BOVILLE, B. W., CRESWICK, W. S. and GILLIS, J. J. A frontal-jet stream cross-section. *Tellus, Stockholm*, **7**, 1955, p. 314 (Figs. 1–3).

† ANDERSON, R., BOVILLE, B. W. and McCLENNAN, D. E.; An operational frontal contour-analysis model. *Quart. J. R. met. Soc., London*, **81**, 1955, p. 588.

with the occluded maritime front had almost disappeared; the jet stream associated with the polar front had strengthened in all parts reaching 210 kt. over the cold-front part of the combined front of the deepening depression centred over Nova Scotia.

Mr. Murray was not convinced of the forecasting value of frontal contour charts. What did they give that could not be obtained from thickness charts? How objective was the analysis from upper air soundings? Mr. Boville said that major prognostic problems reduce to placing the frontal analysis and thermal structure and in getting the upper flow (at 500 and 300 mb.) right. The frontal-contour charts gave a good outline and define more clearly the frontal analysis to begin with. With advection of vorticity aloft and good frontal contrast development would occur. He also described how waves on the polar front go round a block in middle latitudes; only waves on the arctic front would go round a block in high latitudes, vigorous waves on the maritime and polar fronts travelling to the south.

To a question on how he placed a jet-stream maximum wind velocity which had not appeared in any station reports, Mr. Boville replied that jet streams were not transient and the analysis was based on a model where observations were few.

Mr. Illsley drew attention to the similarity between what was called a trowal in Canada and an occlusion in the United Kingdom; an occlusion does not necessarily mean a discontinuity at the surface. Would not a strong front and vorticity be the same as a strong thickness gradient? Do the frontal-contour charts help in forecasting? Mr. Boville though the difference between trowal and such an occlusion might simply be of nomenclature. However, an occlusion, by definition, should not be drawn if not supported by a surface thermal discontinuity. In 1951 there were wide discrepancies in analysis in forecasting offices in Canada; the frontal-contour analysis method has largely eliminated this. In the Central Analysis Office there is analysis and prognosis not forecasting of the weather. A "prognostician" does not analyse. The aim was to get the front right to begin with. He did not believe in the simple concept of upsliding motion on a front; he rather thought that vertical motion should be related to convergence and divergence. He had done no forecasting for four years but outstation forecasters seemed happy with the method.

Mr. Starr asked in what way did a trowal differ from a ridge of warm air aloft. Mr. Boville said they could be the same.

Mr. H. H. Lamb described an X-structure of fronts once used by the United States Weather Bureau with a valley line in continuation of either warm or cold front where the occlusion follows the line of the other front. If the valley line could be equated with Mr. Boville's trowal was the surface part of the occlusion not important in Canada? Mr. Boville said the surface part would be called another front not an occlusion if it had a temperature difference. Mr. Lamb asked if the following of trowals—not associated with a main surface front—settled many forecasting difficulties. Mr. Boville said it did. Mr. Lamb also asked if there were still rain areas not associated with front or trowal. Mr. Boville said not all rain areas were associated with fronts.

Dr. Tucker asked if there was a difference of analysis or merely a difference of nomenclature. Mr. Boville said there was no fundamental difference in the dynamical problem but a difference of approach.

Mr. McNaughton said he was trained as a forecaster in Canada 12 years ago and he had been taught there that the back-bent occlusion did not exist. Now the occlusion itself seemed to be disappearing. He asked for an indication of the density of the network necessary to carry out the three-dimensional analysis. Mr. Boville said the radio-sonde network in the United States and Canada was adequate, the North Atlantic grid of ocean weather ships was fairly adequate and the Pacific Ocean with but one ocean weather ship is quite inadequate. For small details even the United States network is inadequate; the upper-wind network was not so good.

To a question of what is the connexion with thickness-pattern work, Mr. Boville said the 1000–500-mb. thickness was mainly used to study advection. A wave develops with vorticity advection aloft over a strong low-level discontinuity. In the year no serious new development had been missed using these methods. The thickness chart was too gross to give the frontal structure adequately; fronts show up clearly as a shear orientation on wind hodographs over ocean weather stations; the thickness lines mask much of the detail.

Mr. Boyden found the last statement hard to understand. The frontal-contour analysis simply gave the intersection of the front with, say, the 500-mb. surface. Could that not equally come from a horizontal discontinuity in the mean temperature and thermal wind field.

Mr. Graystone thought Mr. Boyden was assuming a constant slope with height; some of Mr. Boville's charts showed it was not so.

Mr. Hawson asked what the evidence was for changing the slope between two stations. Mr. Boville pointed out that the temperature change from the tephigram combined with the wind shear from the hodograph could be used with the thermal-wind equation to calculate the slope and orientation of the front at any point from one radio-sonde and radar-wind ascent.

Mr. Veryard asked what Mr. Boville meant by a front. Mr. Boville said a front satisfied three criteria:

(i) it is a three-dimensional hyperbaroclinic zone with a first-order discontinuity in the temperature and wind fields

(ii) it is a quasi-substantial surface which moves with the wind flow

(iii) it is a reasonably continuous feature of the chart both in space and time.

If these conditions are not satisfied the front is not drawn.

Dr. Sutcliffe remarked that Mr. Boville had used a definition of a front which was both clear and communicable. A front was originally defined as a first-order discontinuity in density, but has since got muddled by the idea of it as a line of cloud and rain—being liable to be dropped if there is no rain. Mr. Boville's definition was more consistent with physical ideas. Meteorologists were partly responsible for the muddle, and would have to un-educate people who now associated a front with rain. Dr. Sutcliffe asked what staff were necessary at the analysis centre; the Central Forecasting Office, Dunstable, had to issue forecasts as well as analyses. Mr. Boville said that in Canada many outstations do no analysis work and receive only local data; all outstations receive facsimile broadcasts of all the charts and prognoses. The Central Analysis Office has two men on each shift for actual analysis and two for prognosis, plus ancillary staff.

Dr. Farquharson asked how long after the data were the charts received. Mr. Boville said that the surface chart was broadcast 4½ hr. after the data to which it referred; the first upper air chart was 5 hr. after the data and the experimental prognostic chart 10 hr. after the data on which they were based. Dr. Farquharson also said fronts could not often be identified above 10,000–12,000 ft. Mr. Boville said the hodograph and tephigram analysis together gave the answer.

Mr. Illsley asked who did the forecasting of the actual weather—the analysis charts shown were uncomplicated. Mr. Boville said the forecasting was done in the field offices. He thought it essential to abandon the simple model relation between surface fronts and rain and cloud and to make more use of fundamental parameters.

Mr. Pothecary said that Meteorological Research Flight data had shown that the humidity field was much more complicated than the temperature field. The upper levels of fronts could be recognized quite easily at 18,000 ft. from the temperature field but the humidity structure depended much more on past history; in some frontal zones the humidity had been found as dry as 5 per cent. even as low as 700 mb.

Mr. Tse Yu-Wai talked about the apparent difference in viewpoint between Canada and the Central Forecasting Office, Dunstable, over the existence of occlusions; he thought that unless we could prove the occlusion does not exist we should assume it does.

Mr. Wallington wondered how much of the difference in idea was due to difference in geography and climate. Perhaps the British Isles would be only a detail to the Canadians. How much of the Canadian work was a change in fashion? Mr. Boville said that size was not the only point of difference; the frontal-contour chart was an important part of the analysis.

Mr. Gold was glad to see the Canadians tackling the problem of analysis in a three-dimensional way and was relieved to hear Mr. Boville speaking about air masses. It was surprising and most encouraging to hear that no major development had been missed; if the prognosis agreed with events (no comparison charts had been shown) then the method was justified. Mr. Gold stressed the trinity of an occlusion (three air masses) and the duality of an ordinary front (two air masses); he thought an occlusion had a reality in the physical constitution of the atmosphere. He was, however, shocked at the disbelief in upsliding motion, an idea which had enabled a forecaster to understand the progressive formation of cirrostratus, altostratus and nimbostratus. He thought the frontal-contour chart an important part of the forecaster's armoury which made clear some of the details of a frontal surface.

Dr. Stagg, in closing the discussion, said that it was not just a comparison of techniques in which Canadian practice differed from United Kingdom practice. It was right to hear from Mr. Boville how other meteorologists think.

OFFICIAL PUBLICATIONS

The following publications have recently been issued:—

PROFESSIONAL NOTES

No. 116—Variations of the measured heights of pressure surfaces. By D. H. Johnson, M.Sc.

The 6-hr. and 12-hr. apparent diurnal variations of the measured heights of standard pressure surfaces have been evaluated for levels up to 100 mb. at Larkhill, Lerwick, Malta and Nicosia. Calculated values of the apparent diurnal variation, based on estimates of the radiation errors

made by Scrase, tend to underestimate the observed variation, but nevertheless provide a reasonable first approximation to the diurnal changes, except for the 2100–0300 G.M.T. variation, when both ascents are made whilst the sun is low in the sky. Tables are given which enable heights of pressure surfaces computed from radio-sonde observations made by stations in the British Isles, Malta and Nicosia to be corrected for diurnal variation.

Handbook of weather messages, Part I, 2nd edn

The new edition of Part I of the Handbook of weather messages contains schedules of reports, forecasts, warnings and analyses broadcast by radio in the United Kingdom, from ocean station vessels and from certain British centres overseas. Times of issue and the frequencies and power used in these broadcasts are given, together with a note of the code forms, and amplifying remarks on the significance of the terms used in the case of plain-language messages, such as gale warnings. Internationally approved numbers, names and co-ordinates of all observing stations used in these broadcasts are listed in numerical order, and a section has been allotted to facsimile transmissions from Dunstable for the first time.

To accord with the practice adopted in Volume A of Publication No. 9 of the World Meteorological Organization station heights for synoptic purposes which have hitherto been the height of the rain-gauge, or the ground upon which the thermometer screen stands for stations without a rain-gauge, are now defined as the height of the barometer cistern above mean sea level.

Part I of the Handbook, like Parts II and III which have already been published, is printed in loose-leaf form to facilitate periodical amendments.

ROYAL METEOROLOGICAL SOCIETY

At the meeting of the Society on December 21, 1955, with the President, Dr. R. C. Sutcliffe, in the Chair, papers were read on convection and on frontal contour analysis.

*Priestley, C. H. B.—Free and forced convection in the atmosphere near the ground.**

This paper was read by Sir Graham Sutton. Sir Graham explained that the paper set out to examine the differences in heat flux between free convection in which the buoyancy force was predominant and forced convection in which convection was produced by the dynamic turbulence of the flow of air over surface obstacles. Using dimensional arguments Priestley had earlier established a formula relating the vertical convective heat flux in free convection to the air density, specific heat at constant pressure, potential temperature, lapse-rate of potential temperature and height. In this paper he postulated that in purely forced convection the heat flux was a function of the Richardson number (R_i) alone and again by a dimensional argument found the form of the function. To examine the validity of this formula he studied a number of observations of heat-flux lapse rate of potential temperature and vertical wind gradient at 1·5 m. made by Swinbank. Plotting heat flux against Richardson number he found that at values of $-R_i$ less than about 0·02 the heat flux was a function of R_i satisfying the theoretical relation for forced convection, and for large values of $-R_i$ the assumption of fully free convection satisfied the values of heat flux better than any other existing law. The transition between the two appeared to be wholly within the range 0·02 to 0·05 for $-R_i$.

In the discussion Dr. Scorer objected to the form of the functions chosen for the dimensional analysis, considering temperature should be used instead of potential temperature. Mr. Charnock spoke on the general applicability of dimensional analysis, and Mr. Craddock described observations on two days at Mauripur, near Karachi, of the entirely different convection patterns occurring on a calm day and on a windy day showing the great difference between forced and free convection.

Anderson, R., Boville, B. W., and McClellan, D. E.—An operational frontal contour-analysis model.†

This paper was read by Mr. Boville of the Central Analysis Office, Montreal, Canada. He explained that it became apparent soon after the Central Analysis Office was founded three years ago that more rigorous methods of frontal analysis than current ones were necessary. The definition of a frontal surface adopted was that it was (i) a three dimensional hyperbaroclinic zone with first-order discontinuities in the temperature and wind fields, (ii) a quasi-substantial surface moving with the wind flow, and (iii) a reasonably continuous feature of the chart both in space and time. The tools used for analysis were charts of contours of the lines in which the fronts intersected the surface, 850-, 700-, 500- and 300-mb. surfaces; and surface, and 700-, 500- and 300-mb. contour charts with, on the upper charts, isotachs at 20-kt. intervals, and vertical cross-sections. The best parameters for representing a front were found to be the orientation given by the hodograph of vertical wind shear, the wet-bulb potential temperature and the saturated wet-bulb potential temperature. In analysis during winter three fronts were recognizable, in roughly south-to-north order, the polar front with tropical maritime air

* *Quart. J. R. met. Soc., London*, **81**, 1955, p. 139.
† *Quart. J. R. met. Soc., London*, **81**, 1955, p. 588.

above and to the south of the front, the maritime front with polar maritime air to the south, and the arctic front north of which was arctic continental air. Some examples of the charts were shown by lantern slides.

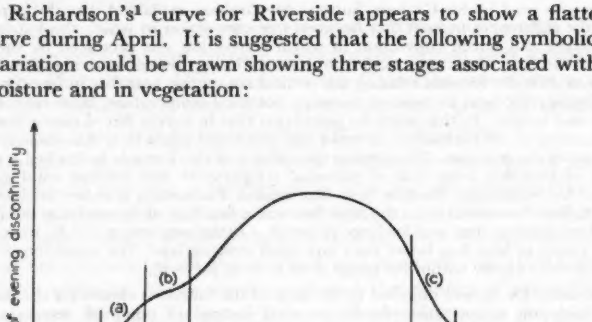
In reply to Dr. Sutcliffe, Mr. Boville said the upper part of the frontal zone was plotted as the front. Mr. H. H. Lamb said the charts showed the amplitude of the frontal "wave" as increasing with height which Mr. Boville said was characteristic of frontal waves. Mr. Boyden thought frontal contour charts showed no more than did the changes of gradient on a thickness chart. Mr. Sawyer inquired as to where the frontal analysis broke down to allow the necessary transformation of air masses, and Dr. Stagg asked on what basis the decision to adopt the frontal-contour method was taken.

LETTER TO THE EDITOR

Night cooling under clear skies

W. E. Richardson's[1] recent paper "Night cooling under clear skies at high-level stations in Cumberland" has been read with interest. It is agreed that owing to the scarcity of observations, the drawing of the 1953 cooling curve for Wahn[2] over the months of May and June is open to doubt. However the 1952 curve[2] confirms a significant change in the slope of the curve of annual variation of the time of discontinuity in evening cooling during the end of March and the first three weeks of April. Parry[3] found an identical change of slope over the years 1949–53 for Shawbury. Recently a night cooling curve was produced for London Airport, and this curve re-affirmed the levelling out of the change of slope during March and April. In view of this it is felt that the significant change of slope during spring cannot be ruled out.

W. E. Richardson's[1] curve for Riverside appears to show a flattening out of the curve during April. It is suggested that the following symbolic curve of annual variation could be drawn showing three stages associated with changes in soil moisture and in vegetation:



(*a*) Drying out of soil

(*b*) Delaying of the progressive change of time of discontinuity caused by transpiration of moisture from surface vegetation

(*c*) Moistening of soil with onset of winter.

W. J. BRUCE

London Airport, November 8, 1955.

[There appears to be an attempt at compromise in W. J. Bruce's letter between the relative significance of the "early spring late time bulge" and the "late spring early time bulge". Under the circumstance of insufficient suitable data this may be the best approach, but until such data are produced some consideration about the implications of such a compromise may provide valuable discussion.

(a) (b) (c) (d)

The conflict of ideas expressed in mine and Mr. Bruce's papers may be summarized by Figs. (*a*) and (*b*) where the curve represents the expected variation in the time of discontinuity, and the shaded areas show the disputed positions of the spring anomaly. Fig. (*c*) demonstrates the casual implication of the compromise, and Fig. (*d*) shows the possible distribution of areas of anomaly if the following argument is acceptable.

Attention has been drawn[1] to the importance of the spring low-humidity factor. It was considered to be both contributory to the drying out of soil, and significant in itself as an aspect of this subject. The attainment of dew point at 4 ft. above the ground is the relevant issue, and although ground effects will influence this, they need not be dominant as has hitherto been assumed. However if the resultant drying of soil is added to this low-humidity factor then the weight of influence seems strongly in favour of the "early spring late time bulge", but in view of the suggestions of Bruce a minor late spring anomaly may very well exist. This distribution is symbolized in Fig. (*d*).

Perhaps I may be allowed to take advantage of this opportunity to expand upon the idea in my paper[1] that minimum temperatures below about 15°F. appear to be impossible when no snow is lying. In the first place I am indebted to J. Glasspoole for examining the point in the light of observations from other British stations taken during certain recent severe spells. So far he has found no evidence to contradict the statement. Further, the events of March 5, 1953, at Alston are most revealing, for the minimum readings for that night were 16°F. at all three stations (Nether Park, Riverside and Samuel King's School). This was the only occasion in the record when a good radiation night produced no inversion. No snow lay at any height in the district.—W. E. RICHARDSON.]

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NOTES AND NEWS

Snow rollers at Grimsetter

During the heavy snow-falls last winter in Orkney a rather unusual occurrence was observed by several people in Orphir, a district about 15 miles to the west of Grimsetter. At dusk on February 22, 1955 a very heavy snow shower fell in which the snow-flakes were exceptionally large. They were described as being "as big as cigarette cards". There was a light westerly wind at the time. By 2100 G.M.T. the snow shower had died out, the wind became calm and the sky cleared. These conditions continued throughout the night and there was a keen frost.

The following morning lumps of snow were seen lying on the slopes of two small hills. They were very numerous and irregular in size and shape, and on close inspection they appeared flattened as if they had spread out on coming into contact with the surface snow. Some of the lumps were larger than a football, and they were confined entirely to the hill slopes, covering an area of roughly half a square mile. Towards the sea there was an abrupt change from the disturbed snow to the smooth undisturbed snow.

J. C. HAY

Publication of data on solar radiation and intensity of daylight

From January 1956 it is intended to make provision for the publication in the *Monthly weather report* of an extended table of radiation data (Table IIIb). At the same time the table of night-sky observations (Table IIIa) will be discontinued.

The new Table IIIb will permit the entry of mean, maximum and minimum daily values of total radiation on a horizontal surface and diffuse radiation on a horizontal surface for Kew, Eskdalemuir, Lerwick, London (Kingsway), Aberporth and Cambridge. It will also allow the entry of mean, maximum and minimum daily values of integrated illumination on a horizontal surface at the first four of these stations. The table will not be complete at first because the radiation recorders for Kingsway and the illumination recorders for Eskdalemuir and Lerwick are not yet available, and it may be some time in 1957 before they are all installed.

Values of maximum and mean direct solar radiation on a surface normal to the sun at Kew will no longer be published. Direct solar radiation can be obtained from the difference between total and diffuse radiation on a horizontal surface, and, as indicated above, mean values of both these quantities will be published.

It is hoped that this additional information will be of assistance to research workers in the agricultural, horticultural, building and engineering industries.

REVIEW

Report on experiments on artificial control of rainfall at Amboseli, Kenya, and Dodoma, Tanganyika, 1953–54. By D. A. Davies, H. W. Sansom, and G. Singh Rana. *Mem. East African Met. Dep., Nairobi*, **3**, No. 3. 10½ in. × 7½ in., pp. 21, *Illus.*, Nairobi, 1955. Price: 4*s*.

Tropical cumulus clouds were seeded at Amboseli and Dodoma in east Africa, using finely ground sodium chloride (50–75 μ) as the seeding agent. Dispersal within clouds was effected by releasing hydrogen balloons carrying charges of hygroscopic salt into each selected cloud and exploding the charges slightly above the cloud base. The experiments were conducted at Amboseli from October 15 to December 15, 1953 and at Dodoma from January 1 to March 31, 1954, at both places on all occasions whenever conditions appeared suitable. It was not possible to install a satisfactory control grid of rain-gauges, and assessment of the results of the experiments was based mainly on the visual observations of subsequent development of the seeded cloud.

The total number of seedings at the two places was 73, of which 57 succeeded in reaching the target cloud. Of these 57 seedings, it was observed that on 42 occasions rain fell within 13–38 min. after the explosion of the charges.

The rain was light or very light on 36 occasions, moderate on 3 occasions and heavy on 3 occasions, and the duration of the rain varied from 3 to 55 min. The results appear to prove conclusively that the release of these hygroscopic particles into a suitably large cumulus cloud would generally be followed by a light shower.

In discussing what adjustment might be made to the technique to increase amounts of rain the authors suggest an increase in amount of seeding substance and a decrease in particle size to, say, 25 μ; from theoretical considerations they suggest that the total quantity of rain might be about eight times as great with particle size 25 μ as with particle size 100 μ.

We look forward with great interest to learning the results of future experiments which it is hoped may be conducted with a smaller-size hygroscopic particle, and we congratulate the British East African Meteorological Department on the excellence of the work so far carried out.

A. F. JENKINSON

OBITUARIES

Charles William Heinemann.—We regret to report the death of Mr. C. W. Heinemann, formerly Staff Clerk in the Meteorological Office which occurred at the age of 90 years, on November 19, 1955. This removes from the roll of Office pensioners one of its Victorian characters. Mr. Heinemann joined the staff at the Victoria Street Office in October 1880 and resigned on account of ill health in November 1922. For the greater part of his career he assisted in the preparation of the *Weekly weather report* and *Monthly weather report*. He spent the last few months of his service in the British Rainfall Organization.

He is remembered by those who knew him as a cheerful likeable man and a very conscientious worker who was never known to make an error in the computing work. In many respects an individualist, he was an ardent vegetarian and the first man on the Office staff to own a motor vehicle—a tricycle. His hobbies included astronomy and the construction of clocks from spare parts; at one time he owned several good telescopes. Mr. A. T. Bench records that at about the age of 83 Mr. Heinemann cycled several times across London to visit him. In March 1955, to the gratification of his old colleagues, Mr. Heinemann attended the centenary dinner. Mr. Heinemann was unmarried and lived with a sister to whom we express our sympathy at her loss.

Professor W. M. H. Greaves, F.R.S.—We regret to learn of the sudden death on December 24, 1955, of Prof. Greaves, Astronomer Royal for Scotland and a member of the Meteorological Committee.

David H. Owen.—The death of Mr. D. H. Owen of Sparkhill, Birmingham, in November 1955 at the age of 84, brought to a sudden close a long and enthusiastic devotion to meteorology in this country. Mr. Owen was one of the now dwindling company of amateur meteorologists whose meticulous care and faithful service as an observer co-operating voluntarily with the Meteorological Office extended over a period of nearly half a century. His climatological returns began in 1907 and are a valuable contribution to local climatology and in recognition of this he received, in 1954, a presentation aneroid barometer from the Office. His interest in weather commenced at an early age and he had maintained weather notes since 1892 at the same place, contributing daily rainfall observations to the British Rainfall Organization from 1905.

Albert Roy Hosker.—It is with deep regret that we learn of the death, on January 30, 1956, of Mr. Hosker, Scientific Assistant, at the age of 25. Mr. Hosker joined the Office as a Meteorological Assistant in April 1947. He served at several aviation outstations and in o.w.s. *Weather Observer*. At the time of his death he was serving at Ronaldsway. Mr. Hosker has been a member of the Meteorological Office swimming team on several occasions when they have won the Air Ministry Championship. He was also a runner-up in the Civil Service Plunging Championship. He is survived by a widow and an infant daughter to whom the sympathy of all who knew him in the Office is extended.

METEOROLOGICAL OFFICE NEWS

Academic successes.—Information has reached us that the following members of the Staff have been successful in recent examinations:

General Certificate of Education (*Advanced Level*): physics, D. Gibbons; pure mathematics, B. Stapleton and G. A. Unwin.

Ocean weather ships.—The following are extracts from the Master's report of Voyage 67 of the *Weather Observer* when the ship was on duty at Station I.

December 22, 1955. Neptune aircraft from Topcliffe circled the ship using a television camera for the British Broadcasting Corporation, Independent Television Authority and the *Daily Mail*, and dropped five canisters containing mail and a Christmas tree. This was a very welcome thrill and cheered everybody up greatly. We are all most grateful to everyone who made this possible. A padre gave us a 15-min. Christmas message whilst the aircraft was circling.

December 25, 1955. Everybody seemed to enjoy their Christmas at sea; the Christmas dinner was excellent and was a great credit to the catering staff. It must have been good as both the crews told the chief steward how much they enjoyed it.

Social activities.—The staff of the London Airport meteorological office held a dance at the Master Robert Hotel, Hounslow on November 30, 1955. The dance was well attended despite the fact that the 30th was the only occasion during November on which fog had persisted at the airport all day. Headquarters and meteorological offices in the London area were well represented, and a highly successful evening was enjoyed by all.

WEATHER OF JANUARY 1956

The average state of the atmospheric circulation over the northern hemisphere during January was similar to that of the month before. The North American anticyclone was generally very large and strong and centred rather further east than usual, the highest mean pressure being 1029 mb. near Hudson's Bay and the greatest anomaly about +15 mb. over northern Labrador and Quebec. The Azores anticyclone was weak and small, and its usual January extension over Spain into central Europe was very feeble. The Siberian anticyclone was large and strong, but lacked its usual extension towards Europe.

Both in the Atlantic and Pacific the cyclonic activity was concentrated in two widely separate regions over the north-eastern and western, or south-western, parts of the oceans. There were several very deep centres early and late in the month over the sea areas between east Greenland and Novaya Zemlya. A very unusual feature was a low which deepened to about 984 mb. near Bermuda on the 5th with pressure remaining very low in that area for the ensuing three weeks; temperature had previously become unusually low over the eastern United States and this depression drove the very cold air on south into Florida.

Most of the month the pressure and thermal patterns were so abnormal over North America that normal patterns and sequences could hardly be expected to the eastward over the Atlantic and Europe. However, for a week or so from the 22nd to the 27th a former Alaskan anticyclone became quasi-stationary over the central United States, near 90°W.—itself a rare event—and the prolonged southerly advection over the great plains and prairies on the western flank of this system removed the pronounced negative temperature anomaly which had covered the region since autumn. East of this same American anticyclone, the complex of Atlantic lows

began to coalesce and shift bodily eastwards. On the 27th the prolonged high-pressure régime over northern Greenland was dislodged and shifted to Scandinavia. This train of events brought a radical change in the character of the winter.

In the British Isles the weather during the first week over most of England had been dominated by extensive and persistent fog; elsewhere it was mild and dry. A wet cold period, with considerable snow in the north, followed, but the third week was milder and changeable and ended with widespread rain and gales. Mild rainy weather continued for most of the rest of the month, but on the 31st cold easterly winds spread from the continent over most of the country.

The year began with widespread north-westerly gales—a gust of 73 kt. was recorded at Tynemouth—as a depression moved south-eastwards from Iceland to Germany; there was also widespread rain or showers with scattered thunderstorms. An anticyclone from the Azores began to move north-eastwards on the 2nd and became centred over southern England on the 4th; and that night frost and fog developed extensively in east and south-east England and the Midlands. The fog was dense locally and persisted throughout the day in many areas from the 4th to the 6th; on the 5th it covered most of England south-east of an approximate line from the Bristol Channel to Whitby. There were good sunny periods however, especially on the 2nd and 5th, and weather was mild, except in foggy areas, with afternoon temperatures exceeding 50°F. at times in Scotland. Arctic air on the western flank of a depression north of Scandinavia, swept southwards bringing snow to many parts of eastern Great Britain on the 7th, and falls became substantial the following day as a depression formed over the North Sea. Another depression, which deepened unusually quickly as it moved south-east toward Ireland on the 9th, absorbed the North Sea depression into its circulation on the 10th as a belt of snow, heavy in places, spread eastwards. Temperature, which had fallen to 10°F. at Dyce early on the 10th, rose to 40°F. during the day. Heavy continuous snow fell for about 11 hr. in parts of Lincolnshire and lay to a depth of about 15 in., but in southern England it turned to rain, and thunderstorms developed. Thundery showers of rain, sleet or snow continued daily until the 12th. A slight earth tremor was felt in some Midland counties on the 10th. The first substantial rainfall of the year occurred on the 13th ahead of a depression which approached from the south-west; both Plymouth and St. Mawgan had more than 1 in. of rain in 12 hr. Throughout the third week a series of depressions moved eastwards over, or to the north of, Scotland on tracks which became progressively further south. Weather during the first part of the week was changeable, though fairly dry and often sunny in England and Wales, particularly on the 18th when many places recorded more than 6 hr. sunshine, but a depression north of Scotland deepened and gave severe gales on nearby coasts—wind reached 83 kt. in a gust at Lerwick on the 21st—as it moved slowly eastward on the 20th and 21st, and there was widespread and locally heavy rain over most of the country. Considerable rain and snow fell on the 23rd as a depression crossed southern England while in its rear cold air spread southwards to give a fall of temperature of 10–15°F. Frost was widespread on the night of the 24th–25th; at Eskdalemuir temperature fell to 12°F. and did not rise above 26°F. the following day, but milder air, preceded by rain and snow, returned from the south-west on the 25th and spread very slowly northward. The thaw caused extensive floods in counties adjacent to the Severn on the 27th as the melting snow and recent widespread rain caused the river to overflow its banks. Weather was dull and wet from the 26th to the 30th with widespread and heavy rain in places as troughs, associated with a large low-pressure system between Iceland and Greenland, crossed the country; but on the last day of the month a well developed anticyclone over northern Scandinavia started to move south-westward and very cold easterly winds spread across the British Isles.

This changeable month produced the rather unusual combination of high rainfall and an excess of sunshine, but temperature was about normal, except in the extreme north of Scotland, where it was 3–4°F. below average. In Scotland the rather severe weather presented many farming difficulties, though hill sheep have suffered more from the cold high winds and lack of shelter than from lack of grazing. Elsewhere maintenance work on farms and market gardens continued with little interruption, and was so well forward that farmers were able to plan to catch up with arrears from previous years. Cattle, even in the north of England, have been left in pasture longer than usual, thus conserving fodder. Ploughing for spring sowing has continued.

The general character of the weather is shown by the following provisional figures.

	AIR TEMPERATURE			RAINFALL		SUNSHINE
	Highest	Lowest	Difference from average daily mean	Percentage of average	No. of days difference from average	Percentage of average
	°F.	°F.	°F.	%		%
England and Wales ...	58	12	−0·6	167	+3	118
Scotland	56	2	−1·9	106	+2	119
Northern Ireland ...	53	18	−2·1	111	+1	96

RAINFALL OF JANUARY 1956

Great Britain and Northern Ireland

County	Station	In.	Per cent. of Av.	County	Station	In.	Per cent. of Av.
London	Camden Square ...	3·60	194	*Glam.*	Cardiff, Penylan ...	5·02	136
Kent	Dover	5·80	271	*Pemb.*	Tenby	6·03	161
,,	Edenbridge, Falconhurst	5·08	207	*Radnor*	Tyrmynydd ...	8·92	141
Sussex	Compton, Compton Ho.	5·55	175	*Mont.*	Lake Vyrnwy ...	9·37	162
,,	Worthing, Beach Ho. Pk.	5·07	218	*Mer.*	Blaenau Festiniog ...	8·35	82
Hants.	St. Catherine's L'thouse	5·12	207	,,	Aberdovey ...	5·16	133
,,	Southampton (East Pk.)	4·81	180	*Carn.*	Llandudno ...	2·71	112
,,	South Farnborough ...	3·94	189	*Angl.*	Llanerchymedd ...	3·67	116
Herts.	Harpenden, Rothamsted	4·51	218	*I. Man*	Douglas, Borough Cem.	4·28	128
Bucks.	Slough, Upton	3·29	177	*Wigtown*	Newton Stewart ...	3·79	92
Oxford	Oxford, Radcliffe ...	3·91	216	*Dumf.*	Dumfries, Crichton R.I.	3·53	110
N'hants.	Wellingboro' Swanspool	3·80	205	,,	Eskdalemuir Obsy. ...	4·43	82
Essex	Southend, W. W. ...	3·58	245	*Roxb.*	Crailing... ...	1·81	94
Suffolk	Felixstowe	3·45	227	*Peebles*	Stobo Castle ...	2·83	94
,,	Lowestoft Sec. School ...	3·37	202	*Berwick*	Marchmont House ...	2·42	108
,,	Bury St. Ed., Westley H.	3·24	181	*E. Loth.*	North Berwick Gas Wks.	2·13	125
Norfolk	Sandringham Ho. Gdns.	3·34	172	*Midl'n.*	Edinburgh, Blackf'd. H.	1·44	82
Wilts.	Aldbourne	4·86	195	*Lanark*	Hamilton W. W., T'nhill	2·21	67
Dorset	Creech Grange... ...	5·03	154	*Ayr*	Prestwick	2·50	88
,,	Beaminster, East St. ...	5·34	153	,,	Glen Afton, Ayr San. ...	3·66	72
Devon	Teignmouth, Den Gdns.	3·99	137	*Renfrew*	Greenock, Prospect Hill		...
,,	Ilfracombe	5·26	160	*Bute*	Rothesay, Ardencraig ...	3·89	86
,,	Princetown	8·97	112	*Argyll*	Morven, Drimnin ...	4·69	74
Cornwall	Bude, School House ...	3·35	110	,,	Poltalloch	4·24	84
,,	Penzance	6·20	164	,,	Inveraray Castle ...	...	...
,,	St. Austell	5·49	128	,,	Islay, Eallabus ...	5·54	118
,,	Scilly, Tresco Abbey ...	4·21	134	,,	Tiree	3·79	89
Somerset	Taunton	2·98	125	*Kinross*	Loch Leven Sluice ...	3·89	123
Glos.	Cirencester	3·60	138	*Fife*	Leuchars Airfield ...	2·27	125
Salop	Church Stretton ...	4·14	159	*Perth*	Loch Dhu	6·09	67
,,	Shrewsbury, Monkmore	3·07	157	,,	Crieff, Strathearn Hyd.	3·19	79
Worcs.	Malvern, Free Library...	3·92	177	,,	Pitlochry, Fincastle ...	2·80	80
Warwick	Birmingham, Edgbaston	3·61	162	*Angus*	Montrose, Sunnyside ...	3·40	171
Leics.	Thornton Reservoir ...	3·59	181	*Aberd.*	Braemar	3·79	119
Lincs.	Boston, Skirbeck ...	...	...	,,	Dyce, Craibstone ...	3·59	152
,,	Skegness, Marine Gdns.	3·99	231	,,	New Deer School House	4·66	200
Notts.	Mansfield, Carr Bank ...	3·80	177	*Moray*	Gordon Castle	3·27	162
Derby	Buxton, Terrace Slopes	9·02	202	*Nairn*	Nairn, Achareidh ...	1·37	76
Ches.	Bidston Observatory ...	2·94	139	*Inverness*	Loch Ness, Garthbeg ...	...	...
,,	Manchester, Ringway...	4·31	180	,,	Loch Hourn, Kinl'hourn	7·45	59
Lancs.	Stonyhurst College ...	4·59	107	,,	Fort William, Teviot ...	7·15	74
,,	Squires Gate	3·69	142	,,	Skye, Broadford ...	6·11	81
Yorks.	Wakefield, Clarence Pk.	3·50	182	,,	Skye, Duntuilm ...	4·25	80
,,	Hull, Pearson Park ...	4·99	277	*R. & C.*	Tain, Mayfield... ...	3·09	127
,,	Felixkirk, Mt. St. John...	4·80	240	,,	Inverbroom, Glackour...	7·36	137
,,	York Museum	4·11	232	,,	Achnashellach ...	10·50	115
,,	Scarborough	3·57	179	*Suth.*	Lochinver, Bank Ho. ...	5·38	127
,,	Middlesbrough... ...	2·69	168	*Caith.*	Wick Airfield	5·44	221
,,	Baldersdale, Hury Res.	4·06	121	*Shetland*	Lerwick Observatory ...	5·21	122
Norl'd.	Newcastle, Leazes Pk....	3·67	185	*Ferm.*	Crom Castle	2·86	86
,,	Bellingham, High Green	3·09	108	*Armagh*	Armagh Observatory ...	2·09	83
,,	Lilburn Tower Gdns. ...	4·00	193	*Down*	Seaforde	3·68	117
Cumb.	Geltsdale	2·22	79	*Antrim*	Aldergrove Airfield ...	2·88	105
,,	Keswick, High Hill ...	3·44	68	,,	Ballymena, Harryville...	3·54	95
,,	Ravenglass, The Grove	3·42	102	*L'derry*	Garvagh, Moneydig ...	...	...
Mon.	A'gavenny, Plâs Derwen	6·37	172	,,	Londonderry, Creggan	5·21	145
Glam.	Ystalyfera, Wern House	8·24	130	*Tyrone*	Omagh, Edenfel ...	2·92	82

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